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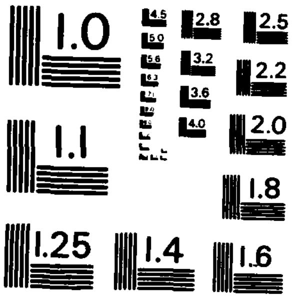


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# STUDIES OF TYPING FROM THE LNR TYPING RESEARCH GROUP

## The Role of Context, Differences in Skill Level, Errors, Hand Movements, and a Computer Simulation


THE LNR TYPING RESEARCH GROUP:

Donald R. Gentner
Jonathan Grudin
Serge Larochelle
Donald A. Norman
David E. Rumelhart





CENTER FOR HUMAN INFORMATION PROCESSING



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# Studies of Typing from the LNR Typing Research Group: The Role of Context, Differences in Skill Level, Errors, Hand Movements, and a Computer Simulation

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## ABSTRACT

This report reviews a large amount of the work on typing done at UCSD by the LNR Research Group. The report consists of five chapters. Chapter 1 is a glossary of terms and a classification of typing errors intended to be used as a standard nomenclature for future work. Chapter 2 is an overview of studies of typing and a brief review of the computer simulation model of skilled typing developed at UCSD (presented in detail in an earlier technical report). Chapter 3 compares skilled and novice performance in discontinuous typing. Chapter 4 discusses keystroke timing in transcription typing, and Chapter 5 discusses error patterns in skilled and novice transcription typing. In general the studies use a variety of methods, including computer simulation, stop-frame video analysis, studies of interkeystroke interval distributions, and analysis of error patterns. Subjects ranged from novice typists (taking a high school typing class) to expert and "super" typists: typing speeds studied ranged from 12 wpm to 112 wpm. The studies help explore the influence of motor schemas and preplanning in the learning and performance of highly skilled motor activities, examine the row of overlapping, parallel motor activity, analyze the significant differences in typing styles, even among typists of equivalent ability, and lead us towards better understanding of the cognitive control systems for complex motor tasks.

**Studies of Typing from the LNR Typing Research Group: The Role of Context, Differences in Skill Level, Errors, Hand Movements, and a Computer Simulation**

The LNR Typing Research Group
Center for Human Information Processing
University of California, San Diego



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# A GLOSSARY OF TERMS, INCLUDING A CLASSIFICATION OF TYPING ERRORS[1]

The LNR Typing Research Group

Donald R. Gentner

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Donald A. Norman

David E. Rumelhart

A common terminology is essential when working in any area, and the study of typing is no exception. To aid ourselves and others, we have compiled a glossary of basic definitions useful in the description of the phenomena of typing. The glossary also contains a categorization of errors. The glossary has proved to be useful in several ways. Not only does it keep our terms consistent, but it has provided a framework for the description and classification of a number of typing errors. We hope this glossary will be of independent use, perhaps leading to standardization of the typing terms used throughout the typing literature.

## Basic Terms: Keystroke, Latency, Interstroke and Interkeystroke Interval

The act of depressing the key on the typewriter keyboard is called the "keystroke." With computer keyboards, this is synonymous with the making of the electrical contact, and the keystroke is assumed (defined) to have zero duration. With mechanical typewriters, there may be considerable duration to the keystroke. The "time" of the keystroke is taken to be the time at which the action is functionally completed, either when the type bar strikes the paper or when the electrical contact on the key is completed.

The term "latency" refers to the time elapsing between the receipt of sensory information and the first keystroke in response. The time from the signal to the first keystroke is the "latency," and the times between successive keystrokes are "interstroke" or "interkeystroke" intervals. In general, the term "latency" is not used in referring to continuous typing, but is reserved for discrete trial paradigms in which a single word or phrase is typed following a signal.

## Digraph and Trigraph

"Digraph" denotes any sequence of two consecutive characters (letters, numerals, punctuation, space, etc.). The term "trigraph" denotes any sequence of three consecutive characters. Although the term "digram" and "digraph" are used synonymously in the literature, we prefer "digraph."

## Terminology for Letter Sequences

Figure 1 shows the Sholes keyboard and the standard (American) mapping of fingers to keys. We classify letter sequences according to the fingers and hands involved. The following four cases are the ones we have found most useful.

2F: sequences in which the letters are all typed on the same hand, but with two different fingers. Thus, ta is a 2F digraph.

1F: sequences in which the letters are typed with the same finger[2] (and therefore, with the same hand). Thus, ceded is a 1F sequence.

2H: sequences that occur across hands. Thus, the is a 2H trigraph.

1H: sequences typed by one hand. This is used when the number of fingers used (1F, 2F, ... ) is not important. Thus, beverages is a 1H sequence.

### Specification of Hand, Finger, and Position: The {H,F,P} Triple

We specify the mapping between fingers and keys by the triple {H,F,P} where:

H specifies the hand (left or right);

F specifies the finger (little, ring, middle, index, or thumb);

P specifies the position, characterized in a coordinate space relative to the home position of the finger, where "up" and "down" correspond to motion along a column and "inward" and "outward" refer to motion along rows, inward being toward the center of the keyboard.

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2. Some of our data (See Genter's chapter, this volume) indicate the usefulness of distinguishing the special case of a 1F sequence in which the same letter is repeated from that in which the same finger types different letters. The most common such sequence is a doubled letter. In these cases, the term "doubles" can be used for the subset of 1F sequences involving the same key, and 1F can then refer to the non-doubled single finger sequences.

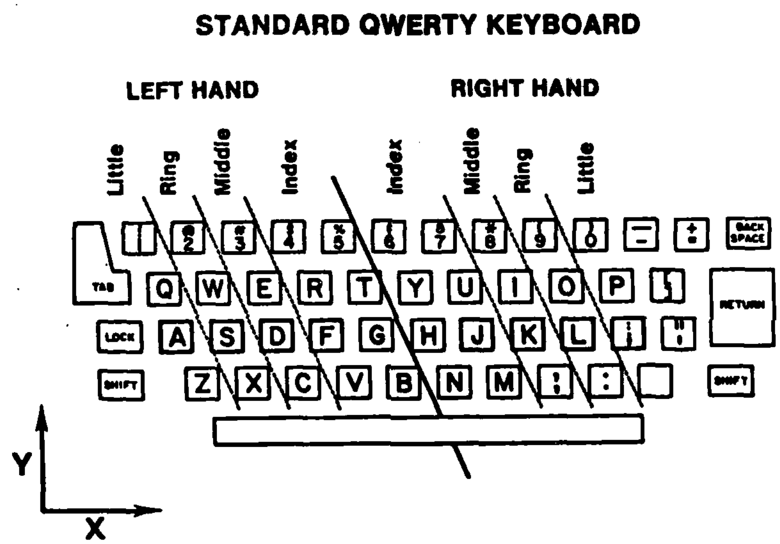


Figure 1. The standard American keyboard (the "Sholes" or "qwerty" keyboard) and the mapping of fingers to keys.

## Terminology for Errors

### Error Categories Based upon the Triple Notation

The {H,F,P} notation (and its application to errors) is useful in distinguishing among some classes of errors. Thus, consider the classes of errors that result from different combinations of errors in the specification of H, F, and P. Let "Ix" refer to erroneous specification of component I, so that {H,Fx,P} refers to erroneous specification of the Finger:

{H,F,P}: In this case, because the correct hand, finger, and position is specified, the correct letter is typed. Nonetheless, four classes of errors fit into this category: "insertion," in which the letter typed does not properly belong in the text; "transposition," in which the letter is typed properly, but it has changed position with the next consecutive letter in the text; "migration," in which the letter moves to an erroneous position in the text; or "interchange" in which the letter changes position with another, non-consecutive letter in the text.

{H,F,Px}: In this case the error is typed with the correct hand and finger, and only the finger position is erroneous.

{H,Fx,P} In this case the error is typed with the correct hand, and the finger moves to the correct position, but the wrong finger moves.

{Hx,F,P}: This is a homologous error, for if only the choice of hand is in error, the letter typed is in the "mirror image" position to the correct one on the keyboard.

### Misstrokes

We define a "misstroke" to occur when the error can be traced to inaccurate motion of the finger, as when one finger strikes two keys simultaneously, or contacts another key in passing with sufficient force to activate it. In all other errors the hand-finger motion appears appropriate for the specification. Misstrokes can best be identified by stop-motion analysis of photographs or video pictures of the hand motions.

### Errors of Transposition, Migration, and Interchange

One major set of errors occurs when the correct letters are typed, but not in the proper sequence. When consecutive text letters are switched, we call it a "Transposition." When two letters that are not consecutive are switched, we call it an "Interchange across I letters," and when one letter moves from its proper position to some other position M letters away, we call it a "Migration across M Letters." (Note that, although an interchange across zero letters and a migration across one letter are identical to a transposition, there are useful

theoretical reasons for reserving the term "transposition" for these cases.)

Transposition errors. A transposition error occurs when two consecutive letters in a word are interchanged, as when the is typed as teh. Transpositions can also occur with the space or punctuation that precedes or follows the word, as when a job is typed as aj ob. Transpositions are classified according to the fingers and hands that are involved. Thus, if kind were typed as iknd, this would be a 1F transposition. If this were typed as tihs, a 2F transposition would be involved. When the is typed as teh, a 2H transposition is involved.

Interchange across I letters. In an interchange across I letters, two non-consecutive letters get interchanged, with I letters intervening (I > 0). The same subclassifications used for transposition errors applies to interchanges. Thus, if major is typed as jamor, this is classed as a 1F interchange across 1 letter.

Migration across M Letters. In a migration across M letters, one letter moves ("migrates") to a new position, with M letters intervening between its correct position and its end position (M > 1). If the word that is typed as atht, this would be categorized as a migration across 2 letters.

## Omissions

An omission error occurs when a letter in a word is left out, as when omit is typed omt.

## Insertions

Insertion errors occur when an extra letter is inserted into a text, as when and is typed asnd. Some insertions can be classed as misstrokes (when stop motion analysis indicates that a faulty finger motion was involved).

## Substitutions

A substitution error occurs when the wrong letter is typed in place of the correct letter. There are several classifications of substitution errors:

Column: When the key for the substituted letter is in the same column as the key for the correct letter and is adjacent to the correct key. Column substitutions are always typed with the correct finger and hand: {H,F,Px}.

Row: When the key for the substituted letter is in the same row as the key for the correct letter and is adjacent to the correct key; There are two cases of Row errors. In one case, the hand and finger are correctly specified, but the position is not, {H,F,Px}. In the other case, the hand and position are correctly specified,

but the finger is not, {H,Fx,P}.

Homologous: When the key for the substituted letter occupies the "mirror image" position on the keyboard with respect to the key for the correct letter, and is therefore typed with the same finger, in the same row, but with the wrong hand, {Hx,F,P}.

Non-specified: When the substitution does not fit one of the above classifications.

## Doubling Error

In a doubling error, a word containing a repeated letter is typed so that the wrong letter is doubled, for example, when book is typed bokk.

## Alternation Error

An alternation error occurs when a letter alternates with another, but the wrong alternation sequence is produced, as when these is typed as thses.

# STUDIES OF TYPING FROM THE LNR RESEARCH GROUP [3]

Donald A. Norman

David E. Rumelhart

## PART I: STUDIES OF TYPING: AN OVERVIEW

The study of typing contains a fascinating mixture of issues from motor skills, typewriter mechanics, anatomy, and cognitive control structures. Our research group initially started to study typing because it seemed an ideal example of highly skilled performance, with readily available experimental subjects and, with the advent of computer controlled keyboards, a possibility of collecting large amounts of response time data. We expected the topic to be interesting, but were unprepared for the complexity of the issues. Typing brings together many different issues, some of them heretofore ignored in cognitive psychology, yet of critical importance in understanding human performance. In particular, some of the problems of typing force us to confront issues of the control structures involved in highly skilled, parallel output performance, as well as issues of the representation of skilled motor acts within the human memory and motor control systems, all of which apply to a much more general range of concerns than simply typing.

In this section we review the work of our research group at San Diego (the group called "The LNR Research Group"). The LNR research group is large, and the work described here represents only a few of the different aspects of typing that we have studied. In general, we have used a variety of approaches to examine typing, including the study of continuous (transcription) typing, discontinuous (discrete trials) typing, the examination of typists of several skill levels, the analyses of errors, of the interkeystroke time distributions, and examination of

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We thank Eileen Conway and Mark Wallen for their continued assistance in all phases of this research. All the members of the LNR research group played valuable roles in this research, but in particular, Donald Gentner, Jonathan Grudin, and Serge Larochelle were important members of the LNR typing group. Craig Will contributed to our early studies of typing. Julie Lustig worked with us in the early phases of the research and served as the typist for the initial film. Sondra Buffett joined later and helped in the completion of the manuscripts.

hand motions through video and film analysis. Several of our studies are presented in detail in the chapters of this volume (see the separate chapters by Gentner, Grudin, and Larochelle and the "Glossary of Terms" to which we all contributed). Here, we review the approach and the different issues that we have studied and present an overview of our typing simulation model.

## Interkeystroke Interval Distributions and Errors

The first thing we did when we started our analyses of typing was to look at the phenomena. As a result, we started to collect interkeystroke intervals for a variety of typists. Much of the early work was simply done in the laboratory by timing the keypresses on the computer terminals that we used in the laboratory and in our offices. Examination of the resulting response time distributions provided some interesting hints of future issues; the distributions showed clear effects of the keyboard layout, and the times for keys typed with the same finger or same hand were clearly different from those typed with different fingers or hands. For a while, we examined almost every conceivable aspect of the distributions, and it appeared that almost daily someone would rush up with yet another set of distributions, looking at specific letter or finger patterns.

At the same time that we were collecting and analyzing distributions, we were looking at the general patterns of typing. We are heavy users of a computer mail system, and this caused us to rely heavily on typed messages for many of our interactions, meeting announcements, and general discussion of issues. Because this form of communication is informal, typists do not always bother to correct their errors, and the error patterns that showed up were quite interesting. Once we realized the importance of looking at typing errors, we requested that people save their errors and forward them to us. Soon we bombarded one another with memos as we discovered more and more interesting errors. The important point was that they were regular, that we could begin to see that they exerted powerful constraints on the set of possible mechanisms. The analysis of the errors led us to some important conclusions about the representational issues that underlie the control of typing movements and that helped dictate the form of our typing simulation model. Most importantly, the doubling error convinced us that the representation could not contain individual "tokens" of each of the letters to be typed, but rather could have only "type" elements. This means that there cannot be any repeated letters in the representation of a string of elements to be typed. This poses an interesting limitation on the representation and, in our opinion, causes the development of a special unit to handle doubles and alternations. Moreover, the existence of doubling and alternation errors indicates that the binding between the unit and its arguments is only weakly specified, leading to occasional errors. We return to these issues later.

## Hand and Finger Motions: Film and Video Analysis

In addition to the study of distributions and errors, we also decided to look at the hand and finger motions in typing. Gentner, Grudin, and Conway therefore arranged to take a high speed motion picture of a skilled typist. The picture was filmed at 100 frames/second and we took considerable care in the filming to use a text that would provide interesting patterns and a camera angle that would yield useful information. The camera was mounted directly over the keyboard, looking down. A front-surface mirror was placed just above the keys so that the single camera frame recorded two views of the fingers, allowing the three-dimensional trajectory of the fingers to be determined. We have since learned that a video camera gives adequate temporal resolution (60 frames/second, or 17 msec.: we use a video camera that has a special, high speed shutter to avoid blur caused by movement). Video analysis has the advantage of allowing immediate playback and, with the use of a video disc, easy stop-frame analysis of the motion. We still use a camera position over the keyboard, with a front-surface mirror to give a second perspective on the movement (although we have modified slightly the configuration first used in the film). (The report of the film analysis is given in Conway, Gentner, and Grudin, 1980, and in Gentner, 1981.)

The movie was a revelation to us, showing that much more was involved than the reaction time distributions could show. Moreover, it emphasized the overlapping nature of the processing. Viewing the film created an immediate impression of a fluid, smooth set of motions, fingers moving in many directions at once. The movement of the fingers over the keyboard reminded us of the movement of sea grass weaving in the waves, gracefully bending this way and that, all in motion at the same time. If we ever believed that skilled typing was a serial process, performed one letter at a time, one viewing of the movie dispelled that belief.

Our analyses of films and videotapes of skilled transcription typists showed that although individual typists exhibited consistent patterns of finger movement and timing, there are large differences between typists that can be independent of overall typing rate. This is discussed in more detail in the chapter by Gentner.

## The Size of the Response Unit

One major issue in the study of typing has been the size of the response unit that governs the generation of the finger movements. In Shaffer's (1973) study of the units of typing for one skilled typist, reviewed in Chapter 1, he had his subject type normal prose, random words, random letters, and foreign words. He found almost no difference between typing prose and random words (the mean interkeystroke interval was 107 msec for prose and 104 msec for random words). Random letters were typed much more slowly than normal text (192 msec), and German text was typed at an intermediate rate (149 msec: the typist didn't know German). Shaffer also found that when look-ahead was limited, the

typist needed to see at least eight letters ahead of where she was typing in order to maintain her normal typing rate. (The rule of thumb that has emerged from this and similar studies is that a typist looks ahead about one second's worth of text: slower typists look ahead fewer letters, faster typists more.) Grudin and Larochelle, in their chapters, further discuss the problem of determining the unit size of typing. They conclude that the unit should be at least the digraph or syllable.

In studies performed by Grudin (1981, 1982: not reported in this book), he discovered that in the typing of transposition errors -- for example, typing waht instead of what -- the interkeystroke intervals are largely as they would have been had there been no error. That is, the timing pattern seemed to be preserved -- an indication that there is some coordinated control of timing for at least two-letter sequences. The explanation most consistent with the data is that skilled typists represent short sequences of letters as a single unit and generate a pattern of timing pulses for each sequence. Additional evidence from the distribution of letter sequences occurring in errors supports this view and suggests that words are parsed into single-letter and two-letter units for execution. Furthermore, Grudin argued that transposition errors were usually errors that occurred within a response unit. This interpretation is further developed in his studies of the errors made by typists of different skill levels, reported in his chapter in this book.

Larochelle studied discontinuous typing, a situation pioneered by Sternberg, Monsell, Knoll, and Wright (1978) and Ostry (1980 and this volume) in which subjects are presented with a single word or word-size letter string and then, upon presentation of a signal, asked to type it. Two different times are important here: the latency, or time from the signal to the first keypress, and the interkeypress interval, the time between successive keypresses. Larochelle found that the changing from words to non-words affected the performance of novice typists, but did not do so for skilled typists, as long as the nonwords preserved the same bigraph frequency as the words. In general, he concluded that the orthographic representation of the letter sequences were still active during the execution of the typing response, and that the transformation of letters into keypresses is a continuing process which overlaps the execution of prior keypresses to a variable degree, depending upon the skill of the subjects and the quality of the material. Novice typists seem to rely on the word structure of the material more than do skilled typists.

Terzuolo and Viviani (1979, 1980) have argued that the unit is the word, and that word-specific timing patterns are stored with each word. Genter (1982), however, shows that their results can be explained by the effects of the contexts for digraphs, and that it is unlikely that the full word is the appropriate size of the unit in typing.

Maybe there is no unit. In fact, there probably is no "unit" of typing control. It is probably no more meaningful to talk about the correct unit size in the case of typing than it is in the case of

reading. In analyses of reading, the interactive models of reading assume that all the various levels of structure contribute to the process: letters, digraphs, syllables, words, phrases, sentences, and so on. It would be misguided to search for a "unit." This is a consequence of any "interactive" type of model. In typing, a similar situation exists. What has been shown is simply that there are are digram frequency effects. All this means is that there are some "top down" effects larger than a single keystroke. We conclude that it is not fruitful to seek out the magical vaue for the size of the response unit. It will surely turn out that responses are determined by a conspiricy of different pressures.

## A Simulation Model of Typing

Our initial analyses of typing, coupled with the understanding of motor processes that was developed through interaction with the "skills" subsection of LNR[4] led us to experiment with possible formal models for the control of movement. The control of the hands is an interesting problem, obviously guided by the cognitive processes of generating words in composition typing and by the reading process in transcription typing. Excellent typists watch the text they are copying from (in transcription typing) not the keyboard (cf. Long, 1976), yet their hands are guided accurately and rapidly over the keys, oftentimes requiring fairly substantial movements to cover the keyboard (especially when typing on the number row, or when typing the "RETURN" key). The timing presents some interesting problems, especially when one hand has a lot to type before the other one, thereby allowing the free hand lots of time to get to the key. Thus, in our film, we observed the typing of the word vacuum, in which the first three letters are struck with the left hand and the rest with the right. While the left hand types vac, the right hand has lots of time to get ready for the u. Indeed, for the film that we analyzed, the hand got to the u key while the left hand was getting to the a key. How did the right hand then know when to do its typing? Did it hover over the key until it got a signal from the left hand that the left-hand sequence was completed? This seemed unlikely because the times involved were too short; with very skilled typists when the two letters being studied are on different hands, the interstroke intervals can be very short, with times occasionally as low as 25 msec and often around 60 msec. The lower figure is less than the neural transmission time for a signal to go from one hand, through the spinal cord to the brain, and back to the finger muscles. Timing by means of feedback did not seem sensible. But how then? Was the timing done by prediction? What if you suddenly slowed up a finger as it was typing -- would this cause the next finger to go out of time? (The answer here is mixed. Grudin's analyses indicate that some transposition errors occur exactly because one finger is slowed up and the other types at its normal time. However, Terzuolo and Viviani (1980) put weights on some fingers and

4. Participants of the skills group, in addition to the two of us, were Amy Geoffroy, Donald Gentner, Jonathan Grudin, Geoffroy Hinton, Michael Jordan, Serge Larochelle, Wynne Lee, Paul Rosenbloom, and Craig Will.

found that although it slowed up those fingers, the typist easily compensated.)

We decided to see if we could derive typing performance without a central timing mechanism. In part, we were captivated by the films that showed the hand configuring itself in preparation for the future keys. Consider how the hand distorts to pick up a piece of paper together with a pencil and a coffee cup. Each of the picking-up motions is different than it would be in isolation as the hand adapts itself to the mutual constraints of the simultaneous tasks. So too with typing -- the hand seems to adopt an optimization for the joint problem of getting to all the keys as quickly as possible, weighted so as to get to the keys in the proper order.

Our solution was based on the relaxation computational methods popular in computer vision. The hands were given the job of simultaneously configuring themselves to get to all the keys, a requirement in which one goal often conflicts with another. In the simulation, the hands move a tiny distance towards each of the goals, in all required directions, with the goals weighted according to temporal order, and with the constraints of possible hand and finger movements being obeyed. Repeated iterations of the small increments eventually leads to a compromise solution in which the hand-finger combination moves as far as possible towards all the targets, but guaranteeing arrival at the next target. From there, we still had to solve timing problems and other issues, but this relaxation iteration formed the basis for our exploration of the typing process. One other major consideration that guided us was our analyses of errors; we wanted a model that both captured the appropriate response timing and also made the same classes of errors that our real typists exhibited. The resulting simulation model proved to be quite accurate, and it has formed a useful basis for the evaluation of our other work on typing.

## Applying the Simulation Model: An Analysis of Keyboards

It seems obvious that the traditional typewriter keyboard -- the "qwerty" or "Sholes" keyboard -- presents many difficulties for non-expert typists. The arrangement of the letters on the keyboard seems arbitrary and difficult to learn (see the discussion in Chapter 1). There appears to be no system to the layout, and beginners often ask why the keys cannot be laid out in alphabetical order. Indeed, a number of typewriter-like devices do arrange the keys in alphabetical order, including children's electronic toys (e.g., Texas Instruments' "Speak and Spell"), hand-held language translators, note-taking devices, and one of the most popular stockbroker's quotation terminal.

Although an alphabetical arrangement might be best for novices, different considerations are relevant for expert typists. Here, one wishes to lay out the keys so as to maximize typing rate. Chapter 1 discusses one major redesign of the keyboard known as the "Dvorak keyboard." This is a keyboard arrangement based upon human factors (time and motion study) principles that emphasizes an efficient layout of the

keys to minimize hand and finger motion (Dvorak, 1943; Dvorak, Merrick, Dealey, & Ford, 1936). Proponents of the Dvorak keyboard have frequently demonstrated advantages in learning time and typing speed, but to little avail against the established dominance of the Sholes arrangement. We decided to examine just how big a difference keyboard layout makes for novice and expert typists.

Different layouts of keyboards produce considerably different loadings of the two hands, as well as different percentages of keypresses required off the home row. Detailed studies of the timing characteristics of typing have shown that between-hand letter digraphs are typed faster than within-hand, and between-finger digraphs faster than within-finger (Gentner, 1981; Kinkead, 1975; Rumelhart & Norman, 1982). These and other factors indicate that for optimum typing speed, keyboards should be designed so that:

A: The loads on the right and left hands are equalized;

B: The load on the home (middle) row is maximized;

C: The frequency of alternating hand sequences is maximized and the frequency of same finger typing is minimized.

The Dvorak keyboard does a good job on these variables, especially A and B; 67% of the typing is done on the home row and the left-right hand balance is 47-53%. Although the Sholes (qwerty) keyboard fails at conditions A and B (most typing is done on the top row and the balance between the two hands is 57-43%), the policy to put successively typed keys as far apart as possible favors factor C, thus leading to relatively rapid typing.

In our studies (Norman & Fisher, 1981), we examined novices typing on several different arrangements of alphabetically organized keyboards, the Sholes keyboard, and a randomly organized keyboard (to control against prior knowledge of Sholes). There were essentially no differences among the alphabetical and random keyboards. Novices typed slightly faster on the Sholes keyboard, probably reflecting prior experience with it. We studied expert typists by using our simulation model. Here, we looked at the Sholes and Dvorak layouts, as well as several alphabetically arranged keyboards. The simulation showed that the alphabetically organized keyboards were between 2% and 9% <u>slower</u> than the Sholes keyboard, and that the Dvorak keyboard was only about 5% faster than Sholes. These figures correspond well to other experimental studies that compared the Dvorak and Sholes keyboards and to the computations of Card, Moran, and Newell (1982) for comparing these keyboards. These correspondences buttress our faith in the veracity of the typing model, and thereby also in its results for alphabetic keyboards.

Thus, the Sholes keyboard actually seems to be a sensible design, superior to all of the alphabetical arrangements that we have studied, and only 5 to 10% slower than the Dvorak keyboard, the one that was based upon time-and-motion studies.

For the expert typist, the layout of keys makes suprisingly little difference. There seems no reason to chose Sholes, Dvorak, or alphabetically organized keyboards over one another on the basis of typing speed. It is possible to make a bad keyboard layout, however, and two of the arrangements that we studied can be ruled out. One of the slowest keyboards is the configuration of keys that people think of when considering alphabetical arrangements.

## PART II: SOME BASIC PHENOMENA [5]

### The Timing of Keystrokes

World champion typists can type at rates up to 200 words per minute. This involves a mean interval between key strokes of 60 milliseconds, close to the the neural transmission time between the spinal cord and the periphery (and obviously, many keystroke intervals will be considerably less than the mean). There cannot be much feedback between strokes being performed so rapidly. Even relatively ordinary typists can routinely generate keystrokes at rates almost as rapid as this. For example, of the 1656 times th was typed by one of our subjects, 414 times the interval was less than 63 msec. The th interkeystroke interval was less than 75 msec half of the time.

Speed, however, is the simplest of the phenomena that need to be accounted for. Overall, the timing phenomena that provide strong constraints on the structure of a possible model of typing include that:

(a) People can type very quickly;

(b) Cross-hand interkeystroke intervals (2H patterns) are shorter than those within hands (1F and 2F);

(c) Within-hand interkeystroke intervals appear to be determined by the patterns of fingers that are involved (i.e., doubles, 1F, and 2F) and by the reach from one key to the next;

(d) The time for a particular interkeystroke interval can depend on the context in which it occurs.

5. This section is adapted from Rumelhart & Norman (1982).

## Pattern of Errors

Errors are of special importance, for some of them give strong clues as to the underlying mechanisms. Thus, the existence of transposition, doubling, and alternation errors has played a major role in determining the structure of the model.

### Transposition Errors

One of the most common and most interesting categories of errors is transposition, the reversal of two adjacent letters. The large majority of these errors occur across hands. Shaffer (1976) reports that of his subject's transposition errors, about 90 percent were cross hand transpositions. We find the number to vary, being only 75 percent for one of our skilled typists. Examples of transpositions from our data include:

because -> becuase
which -> whihc

Of the within-hand errors that we have examined, half involved adjacent keys (such as e and r and o and p ), as in

supremely -> supermely

One interesting example was reported by Shaffer (1976):

went down -> wne todnw

the four keystrokes on the right hand (the n, space, o, and n ) have all been displaced with respect to the five left hand keystrokes.

### Doubling Errors

When a word contains a doubled letter, the wrong letter is sometimes doubled. Thus, look can become lokk. This error was pointed out by Lashley (1951) and by Shaffer (1976) as being diagnostic as to the nature of motor control. Although our corpus of transcription typing only includes one example of a doubling error of this sort

school -> scholl

we have collected many doubling errors from our samples of composition typing (while using the laboratory computer). For example:

gibbs -> giibs
Screen -> Scrren

### Alternation Reversal Errors

These are akin to the doubling error, but with an alternating sequence. Thus in the word these the ese is an alternation. Samples observed during composition typing include:

these -> thses
there -> threr
were -> wrer

Other Errors

In addition to the errors of transposition, doubling, and alternation, a number of other forms of errors occur. A large proportion of these errors are described and defined in the Glossary of Terms (The LNR Typing Research Group, this volume) and in Grudin's chapter (this volume), so there is no need to repeat them here. We believe that some of these errors come from factors outside of the control of hand movements, either in the cognitive factors determining the choice of response schemas or in "slips" of performance, as discussed by Norman (1981).

## The General Organization of Typing

Finally, there are two other observations that we have used as strong constraints: the overlapping of hand movements and the unit of organization of the strings to be typed.

Skilled Typists Move Their Hands toward the Keys in Parallel

We have already mentioned the filming of hand movements that we have conducted using high speed motion pictures and stopped-frame video analysis. The results of these studies show the fingers of the hand in almost constant motion, with fingers starting to move toward their destination before the several preceding characters have been typed. A serial model of typing in which each finger in turn makes its stroke is incorrect. Rather, there seems to be a coordinated structure that allows the control of several fingers simultaneously.

# PART III: A COOPERATIVE ALGORITHM SIMULATION MODEL OF TYPING[6]

In this section we describe the operation of a working computer program that models a skilled typist. The program development was guided by the considerations of typing performance that we have just discussed. This section tells of the actual implementation. The completed model simulates a skilled human typist. The model output is both a set of keypress intervals and also a graphic display of the hands moving across the keyboard.

Control of the fingers poses a number of complexities, and the cognitive specification of the actions to be performed must be compatible with both the existing knowledge of mental structures and of the phenomena of typing, especially the factors discussed in the previous sections. Our analyses of these issues lead us toward a model that has the following properties:

6. This section is taken from Rumelhart & Norman (1981 and 1982).

(a) Control of action sequences by means of schemas;

(b) Selection of appropriate motor schemas through a combination of activation value and triggering condition;

(c) The representation of letter typing by means of a <u>pure type theory</u> (i.e., one with no type-token distinction);

(d) The need for distributed (local) rather than concentrated (central) control of movement.

We start with the assumption that motor control of a learned movement is represented by means of a motor schema, an organized unit of knowledge, differing from the form of knowledge widely studied in the literature on memory, language, and thought only in that it has as its output the control of body movements. This is not a new concept. Actually, the term "schema" was originally introduced into psychology for the use in skilled motor control by Head (1926) and is still used for that purpose (cf. Schmidt, 1976).

We propose that one of the functions of schemas is to act as motor programs. The term "motor program" is to be understood by analogy with the term "computer program." We believe there has been some confusion in the literature on skills in this regard, with critics of the notion of motor programming acting as if a program were a fixed action sequence, specified in complete detail before the actual movements. According to our view, motor programs are flexible, interactive control structures, capable of calling upon sub-programs, passing parameters to be bound to program variables, and making local decisions as a result of current conditions (which might include information from feedback channels, from perception, or other sources of knowledge). A motor program is not a fixed action pattern of movements. It is a set of specifications or control statements that govern the actions that are to be performed, with considerable flexibility in the specification of the actions. A program specifies the rules that are to be followed in the action, not the actual motions.

## Issues Not Covered by This Simulation Model

Typing is a rich, complex skill, and although we examine and model a number of the characteristics of skilled typing, there is also much that we do not cover. We look only at skilled typing, and cover neither the mechanisms used by inexperienced typists nor the mechanisms involved in learning. We assume that all the necessary control and knowledge structures are already established. We do not examine how a skilled typist might vary typing rate in order to manipulate the speed-accuracy tradeoff (although there are several parameters of our model that can readily be identified as potential candidates for this manipulation). We do not look at the mechanisms involved in perception or the encoding of the strings to be typed, nor in monitoring the accuracy of the typing. We do not simulate the deterioration of typing rate that occurs as

the text is modified from normal prose to non-language or random letters. Finally, we only study lower case aphabetic characters and a limited number of other keys, ignoring most non-alphabetical keys.[7] Our work is readily extended to these other keys, however, so we do not consider this of fundamental importance. However, there are insufficient data available for these other keys, and in many cases, the keyboard locations are not standardized, so that typists are not as expert with them (or, as is often the case with number keys, may prefer to adopt a different mode of typing for them). Despite these omissions, there still has been considerable work for us to do.

## The ATS Formalism

The basic framework that we follow is called an Activation Triggered Schema system (ATS). The model consists of a set of schemas, each with activation values. A schema has an activation value that reflects the total amount of excitation that it has received. The normal, resting value for a schema is zero. It can increase when the schema is "activated" or decrease when the schema is "inhibited." Schemas interact with one another, and the activation value reflects this interaction, as well as the effects of decay and other sources of activation and inhibition. When appropriate conditions have been satisfied, a schema may be "triggered," at which time its procedures become operative and control whatever operations they specify.

Different schemas are often interconnected. Moreover, one schema may call upon other schemas to perform specific tasks, much as a computer program calls upon subroutines or coroutines. When one schema calls upon another, the initiating schema is called the "parent schema" and the called schema is the "child schema." Each schema can serve in any or all of three ways: as a program in control of operations, as a parent schema that initiates the operation of other schemas, or as a child schema, invoked by a parent.

A particular schema might be invoked by a parent schema, set into motion some operations, and then itself serve as a parent to its child schemas. Usually, but not necessarily, when a child schema has completed its operations, control returns to the parent schema. Thus, the schema for typing the word the might be initiated by the triggering of the parent schema for the, which then controls the activation and triggering of the child schemas for the letters t, h, and e, that in turn activate the child schemas that control the actual finger, hand, and arm movements.

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7. In all of the analyses of typing data discussed in this section, we look only at lower case alphabetic characters, spaces, and limited punctuation (period, comma, and semi-colon). Other non-alphabetic characters, punctuation, numerals, and the use of the RETURN and SHIFT keys are not examined.

## The Simulation Model

Figure 2 illustrates the basic structure of the model. The model incorporates the ATS system plus specific control mechanisms for the activations and selection of particular hand and finger movements. The input of the model is a string of characters that constitute the text to be typed. The output is a sequence of finger movements, either displayed on a visual computer-controlled display as the movement of the hands and fingers over a typewriter keyboard, or as a series of coordinate locations for the relevant body parts.

Figure 3 illustrates the basic assumptions of the activation process using the word very as an example. First, the schema for the word is activated by the perceptual system and parser. This, in turn, activates each of the child schemas for keypresses. Each keypress schema specifies the target position, with position encoded in terms of a keyboard centered coordinate system. These target positions are sent to the response system which then must configure the palm and finger positions properly. Each keypress schema inhibits the schemas that follow it. This means that proper temporal ordering of the keypress schemas is given by the ordering of the activation values. In addition, the activation values are noisy, which leads to occasional errors.

The response system feeds back information to the keypress system about the current location of the fingers. Whenever the current finger position is within some criterion distance of its target position, and the relevant schema is the one most highly activated, then the triggering conditions are satisfied and the actual keystroke is launched.

## Repeated Letters Imply That There Are No Token Schemas

The existence of doubling and alternation errors poses special problems. Consider the word book. According to the arguments we have just presented, the word would be represented by schemas for each of the letters: b o o k. It is easy to see how such a representation could lead to transposition errors (such as boko ) but not to doubling errors. It would be easy to make up a schema for a doubled letter (so that the word would be represented by the schemas b DOUBLE-o k ), but this would not lead to the doubling errors either.

The doubling error turns out to have two major implications. First, it implies that there are special schemas that signal the existence of doubled letters, and that occasionally these schemas get applied to the wrong letters. In computational terms, this means that the binding between the arguments of the special schemas for doubling occasionally get made improperly. Second, the need for a special schema to mark doubled letters implies a difficulty in having the regular letter schema signal the double. Why isn't the word book represented by the schemas b o o k ? The reason would seem to be that this would require two instances (tokens) of the schema for o; the existence of the doubling error implies that such repeated tokens of a schema are not possible.

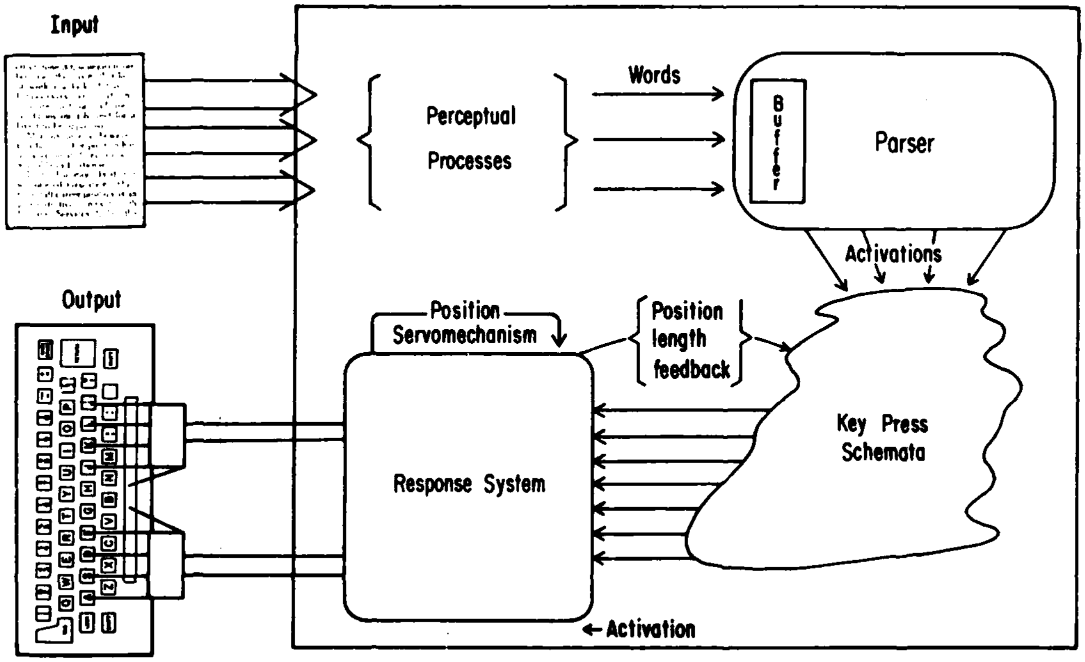


**Figure 2. The information processing structure used by the simulation model of typing.**

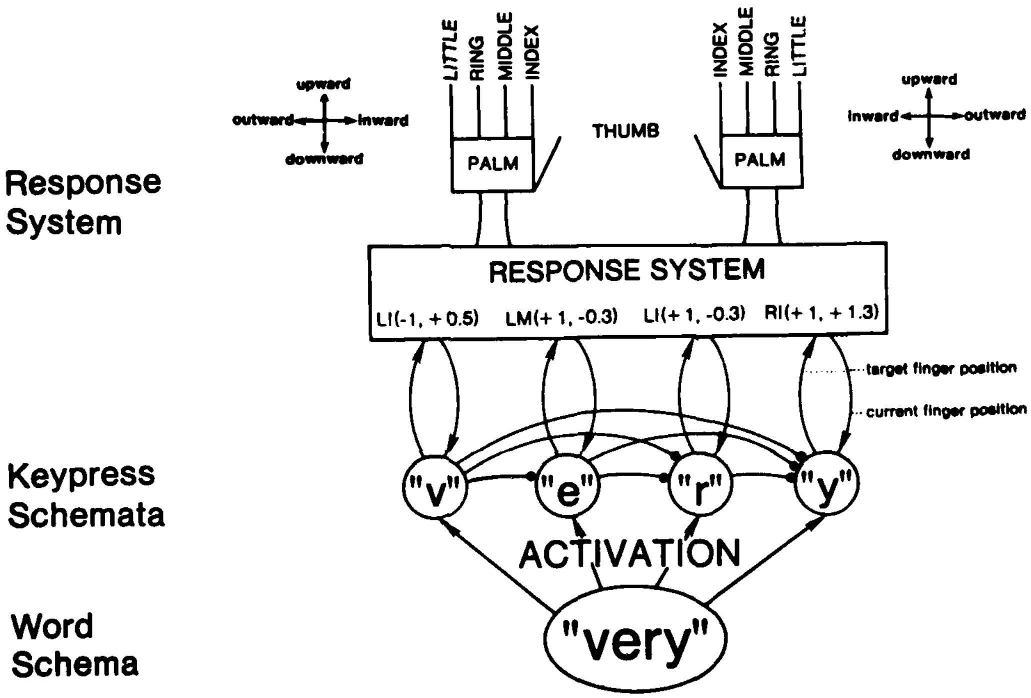


Figure 3. The interaction of activations when the word very is to be typed. Inhibition is shown by the lines with solid circles at their termination.

Thus, the existence of doubling errors forces us to a pure "type" model, in which each letter can only have a single keypress schema; the keypress schemas exist only as "types," with no "token" schemas. There must be a special schema that signals the presence of a doubled letter. Moreover, there must be a weak binding between the special schema and the arguments upon which it operates. In the model, the arguments are not bound to the schemas, but are established via activation values. The most highly activated keystroke schema is triggered when it is within a criterion distance of its target. After triggering (and the resulting launch of the keystroke), this keypress schema can become "bound" to a doubling schema if one exists with a higher activation value than its own. Because activation values are noisy, occasionally this leads to errors in the linking of keypress schemas to a doubling schema.

The existence of alternation errors leads to the same conclusion: there must be a special schema that signals the presence of alternating letters, with a weak binding between the schema and its arguments, and the mechanism proposed for alternations is similar to that for doubling.

Here is an example of the typing of a word with a doubled letter. The word book is represented by the activation of four schemas: b DOUBLE o and k. Each schema inhibits all that follow it, in the regular fashion. The operation now is much as we illustrated before, except that after a keystroke schema has been triggered, it checks for the existence of a double schema whose activation value exceeds its own value. The b will initially be the schema most highly activated, and when the finger gets within a criterion distance from the key, the b keystroke will be launched. Now the DOUBLE schema will have the highest activation level. However, the DOUBLE schema does not command any motor responses, and it allows control to be passed to the schema with the next highest activation value. The next schema is the one for o. It proceeds normally. As the keystroke is launched, the o schema notes that there is a DOUBLE schema whose activation value is greater than its own. Whenever this condition occurs, the keypress schema deactivates the DOUBLE schema and, after the keystroke, does not deactivate itself. As a result, at the completion of the keystroke, the schema is again triggered, launching itself a second time. At the launching of this second keystroke the doubling schema is no longer present, so that typing of the rest of the word can continue. Noise in the activation levels occasionally causes this mechanism to go awry so that the DOUBLE schema gets associated with the wrong keypress schema, causing the wrong character to be doubled.

This mechanism for doubling errors is, then, the same as the mechanism for transposition errors, except that here, one of the two schemas that get transposed is the one representing "DOUBLE." By this model, therefore, in a word like book, the underlying schema representation is b D o k (where D stands for DOUBLE), and so, if any pair of schemas could transpose, we would expect the following typing sequences to be possible:

| transposed schemas | resulting schemas | typed string |
|---|---|---|
| none | b D o k | b o o k |
| b - D | D b o k | b b o k |
| D - o | b o D k | b o k k |
| o - k | b D k o | b k k o |

Because the doubled letter results from explicit application of the DOUBLE schema, we would therefore never expect to see an error of the form boko, where one of the pairs of the doubled letter transposes with another. This is simply not possible in our model. In principle, this provides us with a strong test of the model, however in practice, the frequency of doubled letters is so low as to make critical tests unlikely without some artificial means for increasing the frequency of doubles or a massive study of large quantities of text.

We suspect that errors of alternation are caused by an underlying representation and mechanism similar to that proposed for doubles. Thus, a word such as where would be repesented as w h A e r (where A stands for the schema for ALTERNATION of the two letters that follow). By the same transposition argument as used with doubles, this mechanism should lead to the following sequences with the word where:

| transposed schemas | resulting schemas | typed string |
|---|---|---|
| none | w h A e r | w h e r e |
| w - h | h w A e r | h w e r e |
| h - A | w A h e r | w h e h r |
| A - e | w h e A r | undefined |
| e - r | w h A r e | w h r e r |

Because there is only a single representation of the letter being alternated, we should not expect the alternating letter to be split, so an error of the form wehre is not possible with our model.

When we added this alternation mechanism to a version of the model, it led to difficulties. These were primarily with the typing of spaces. Let the symbol - stand for space. Words such as -a- that had but one letter were spelled a-a rather than -a-. It is possible that the problem here lies with the parsing mechanism, not with the alternation schemas. It is probably wrong to treat a word such as a or I as an alternation of space letter space (that is, as the schemas A space letter) but rather, each word should either be followed or preceded by a space (so that only a single space is ever tied in with a word). Because we did not attempt to model the perceptual and parsing process, we did not pursue this possible explanation. In similar fashion, in our list of possible alternation errors for the word where, transposition of the A and e schemas for where (yielding the schema sequence w h e A r) is undefined, because the alternation schema A requires two arguments. In our simulation model, the space following the word was picked up as the second argument, leading to the typing of the string wher-r. In our data, we never observed errors of this form, where spaces were part of an alternation sequence.

The assumption that there are no "token" nodes causes special problems for any word that contains repeated instances of the same letter that is not part of a double or an alternation (e.g., the _e_ and _p_ of _perception_). As a result, if a word contains a repeated instance of a letter, at the first instance of the letter, (say, the _e_ in _perception_) the keypress schema for _e_ becomes activated and therefore cannot be used to encode the repeated instance of the _e_ until it has completed its duties (i.e., until _pe_ has been typed). Parsing of the word into keystroke schemas is blocked at the repeated letter until the keystroke for the previous instance has been completed. Thus, the parser sets up the keypress schemas for _p_, _e_, _r_, _c_. When the _p_ and _e_ have been typed, the parser is then free to set up the rest of the word: _e_, _p_, _t_, _i_, _o_, _n_. A similar blocking occurs in the case of repeated doubles, as in _bookkeeping_. Because there is only one node for DOUBLE, the parser can at first only set up _b_, _DOUBLE_, _o_, and then, when the doubled-o has been typed, can add _DOUBLE_, _k_, and finally, when the doubled-k has been typed, _DOUBLE_, _e_, _p_, _i_, _n_, _g_.

## Movement

In the model, each active schema pushes its relevant hand and finger toward its desired key at the same time, and the final overall configuration is determined by the competition among these forces. Each schema pushes with a force proportional to its activation level. As a result, the forces are weighted so as to cause the letter schema that is next in line to be typed to approach its key most quickly. The actual location of each finger is determined by the sum of the extensions of the finger and the hand. To type a particular typewriter key, it is only necessary that the end position be correct. The endpoint configuration is reached through an iterative relaxation process that only involves local computation. Because of the unequal weighting of activations, the process will eventually cause the most highly activated schema to move its finger-palm configuration to within a criterion distance from its target key, satisfying the trigger conditions and launching the keystroke. A more complete description of the model operation can be found in Rumelhart and Norman (1982).

## Appraisal

In order to evaluate the model, we gave it a text of slightly over 2,000 words to type. The pattern of keystrokes and times were collected from the simulation and analyzed in exactly the same fashion as we had analyzed the data from our human subject. Overall, the fit of the model to the many phenomena of typing is good. Detailed analyses of the model performance indicate that the simulation results do show about the right pattern of interstroke intervals. Moreover, the correlation of model times with actual typing times for the 66 most common bigrams from our data with the data of 6 subjects yields an overall correlation between the model and the averaged data of about 0.86. The fit is not bad; however, the model clearly does not account for all that is happening. (Data for 5 of these subjects were collected by Donald Gentner. A more complete appraisal of the model is given in Rumelhart & Norman, 1982.)

The model does produce errors in typing, the most important ones being transposition errors, doubling errors, and misstrokes. The proportion of errors in the model is determined by the amount of noise in the activation levels. In our subjects' data we observed transpositions at about a rate of 1 for every 1800 keystrokes. We adjusted the noise level to yield errors at a rate of about 1 for every 30 keystrokes. Despite the large difference in rate, the basic pattern of errors is similar. For example, a large majority (76%) of the transpositions in the simulation occur across hands. This is about the same as our subject and comparable to values reported for others. At the level of noise employed in the simulation, 17 doubling errors were generated.

## Conclusion

We have constructed a working computer simulation of a model that captures the appropriate spirit of the phenomena observed with human typists, although it does not yet offer a complete account of the typing process. Despite the lack of an internal clock or "metronome" for timing, the model provides a reasonably good account of the timing patterns observed among skilled typists, including the prediction of negative correlations among successive keystrokes, a characteristic of metronome models (see Chapter 1). In similar fashion, there are no specific context dependencies built into the model and yet the time that it takes to strike keys depends upon the context in which they occur. We have no specific stored timing patterns for specific words, yet the model predicts that words have characteristic time profiles. We have no specific mechanism for transposition errors, yet our model generates the correct types of transposition errors. Moreover, the co-ordinative structure assumed within the model yields a qualitative emulation of the pattern of overlapping movements shown in a high speed film of a typist.

A number of conclusions can be drawn from our studies. First, the existence of doubling errors strongly implies the existence of a pure "type" representation of the keyboard schemas, with their arguments only loosely bound. Second, the nature of the skill requires simultaneous, parallel control of the fingers and hands, and this requires some form of negotiation process to turn the potentially competitive movements into cooperative ones. The degrees-of-freedom problem can be turned into a degrees-of-freedom virtue. Third, the model must incorporate the entire environment within which the typist operates, from the reading of the text, to the cognitive and motor control systems, to the shapes and mechanical characteristics of the hands, finger, and keyboard. Indeed, some of the limitations of the current model may really result from limitations of how well we dealt with the environment surrounding the control processes. Perhaps the central conclusion to be drawn from our analysis of typing deals with the nature of skilled motor co-ordination. We propose that the motor control system carries out its computations relatively locally and in parallel. We presume that such a conclusion will be proven for all skills involving high speed performance.

We consider that the typing simulation provides a useful first order approximation to the final model of typing. This model demonstrates that many of the phenomena of typing can be reasonably well described by a structure that allows for parallel movements of the fingers, with no central timing mechanism. In normal operation, the timing is completely determined by how long it takes each finger to reach its target position and for the inhibition from preceding fingers to be released. Thus, the timing is determined primarily by the physical constraints on finger and hand motions and by the mechanical layout of the keyboard.

Although the model works quite well, there is need for a revision, to a large extent because of the work reported in the chapters by the other members of the research group -- Gentner, Grudin, and Larochelle. Among other things, a model of typing will have to account for the overlapping of preparation and execution, for the different effects of orthographic variables on the performance of skilled and novice typists, and for the spelling and timing patterns of errors. The result implies considerable structure in the internal units that guide the typing, with top-down effects taking place over groups of at least more than one or two letter units, but smaller than most words. A central timing mechanism does not seem to be necessary, but consideration of the role of the perceptual and working memory processes is probably necessary to account for the timing patterns.

Our computer simulation of typing does not satisfy all of these requirements and the model is inadequate in some of its features and assumptions. However, it serves as a useful first approximation for the understanding of skilled typing. In the earlier section on the LNR approach we concluded that it was not fruitful to search for the magical value for the size of the response unit. It will surely turn out that responses are determined by a conspiricy of different pressures. Some of the pressures will be those well described by the model. Others of them will depend on other aspects of experience and the context. There are two points to be made here. Many things which one might have thought were the products of central control could have been generated by local interactions (as in the typing model). Some things that are observed such as frequency effects probably are the result of top-down processing forces. Presumably, were we to carefully design our experiments we could find other more subtle top-down effects. Some of the observations of the LNR group on error correction might suggest that there are syntactic and semantic effects, but we would not want to conclude that the sentence was the response unit. Nevertheless, it should not shock us to find that such things did have an effect (albeit subtle). Perhaps the suprising thing is not so much that there are traces of top-down effects, but at how difficult it is to find and document them. The difficulty probably comes from our experimental methodology. Clever experimentation (rather than the largely observational techniques we have thus far employed) will probably reveal more such effects in the future.

# A COMPARISON OF SKILLED AND NOVICE PERFORMANCE [8] IN DISCONTINUOUS TYPING

Serge Larochelle

Much of the fascination with skilled activities has to do with the speed achieved in expert performance. By comparison, the slow and stumbling performance of novices seems rather bland and uninteresting. This may explain why most previous research devoted to transcription typing has been focused on the performance of skilled subjects. As a result, we have a much poorer characterization of the properties of novice typing. The problem is that, without such a characterization, it is difficult to determine how expert speeds are achieved. The major motivation for the following studies was to step out of this vicious circle. In these studies the temporal properties of skilled and novice typing are compared and an attempt is made to specify some of the differences in processing which distinguish skilled from novice performance.

The studies are based on the discontinuous typing paradigm, used previously by Ostry (1980), and by Sternberg, Monsell, Knoll, and Wright (1978). In the discontinuous typing task, the subjects are presented with isolated words or word-size letter strings, which they are asked to type, on cue, as fast and accurately as possible. The variable of primary interest is the average time interval between the successive keystrokes. However, there is another temporal variable involved in discontinuous typing experiments, namely: the time between the signal to respond and the first keystroke (hereafter referred to as the latency period).

By its very nature, the discontinuous typing task deals with the transformation of lexical-orthographic information into an action sequence. The potential influence of syntactic and semantic factors on typing performance is eliminated altogether. However, the evidence accumulated so far indicates that the syntactic and the semantic structure of the material contributes very little to skilled performance in continuous transcription typing, as noted in Chapter 1. For instance, Shaffer and Hardwick (1968) failed to find any speed or accuracy difference between prose passages and passages made of a random distribution of the same words. By contrast, they found a deterioration in performance when the material was made from nonsense letter strings.

Similarly, in the discontinuous typing task, Sternberg, Knoll and Wright (1978) found a difference in average interstroke interval between words and nonsense strings. However, they did not find the frequency of the digraphs composing the nonsense strings to have any effect on skilled performance. This lack of effect is somewhat at odds with results obtained in continuous typing experiments. For instance, in the previously cited experiment by Shaffer and Hardwick, a gradual

deterioration in skilled performance was observed as the quality of the typing material was degraded from words to syllable strings to first and zero-order letter strings.

Because of the neglect of novice performance which was previously alluded to, we still do not know the role of syntactic and semantic structure in novice typing. We do know, however, that novice performance, like skilled performance, suffers from manipulations which destroy the word structure of the typing material. The problem one faces in evaluating the results is that the manipulations involved were rarely the same across skill groups, or that these manipulations were too radical to provide a good insight into the nature of the processes at work (Shaffer & Hardwick, 1970). By contrast, the stimulus strings used in the first experiment reported here are rigorously controlled, with very graded variations in their frequency composition. The experimental conditions are also the same across skill groups.

In order to get a more detailed view of the processes by which strings of letters are transformed into sequences of keystrokes, the motor composition of the sequences is also varied. It has been repeatedly shown (with skilled subjects again) that sequences of keystrokes which involve fingers of different hands (2H) are executed faster then sequences which involve different fingers of the same hand (1H). The first experiment deals with 1H and 2H sequences of different lexical-orthographic composition. The second experiment focuses on single-hand sequences, the analyses bearing on the results obtained with keystroke transitions which involve the repeated use of one finger (1F) and those which involve two different fingers (2F).

## Experiment 1

### Method

Subjects. Twelve right-handed subjects participated in the experiment. Four of them were skilled typists. These subjects were by no means experts. Their typing speed ranged from 65 words/min. to 73 words/min., with an average of 70 words/min. (171 msec/keystroke). Similarly, the eight novice subjects were not true beginners. They were college students who had learned the touch-typing method in high school. They had not reached a very high skill level then, nor had they practiced much since then. Their average typing speed was 21 words/min. (571 msec/keystroke), with a range going from 15 words/min. to 26 words/min.

Stimuli. As mentioned previously, one set of stimuli consisted of letter strings which could be typed with the fingers of one hand (1H strings). The letter strings in the other set required a strict alternation between the fingers of each hand in executing the successive keystrokes (2H strings). The same letter could appear more than once within a given stimulus string but not in consecutive positions. About half of the 1H strings were typed by the right hand and the other half by the left hand. Similarly, among the 2H strings, about half of the

strings started with the right-hand key, the other half starting with a left-hand key. In order to equate as much as possible the amount of work done by the left and the right hand, the letters a, z, x, and c were excluded from the composition of the strings because, on the standard Sholes keyboard, there are no letters in the corresponding positions under the right hand.

The stimulus strings were of three different categories with respect to their orthographic composition. First, there were words 3 to 6 letters long. Second, for each string length, a set of "pseudowords" was constructed by recombining the letters found in the set of words of that length while trying to preserve as many of the same digraphs as possible. No attempt was made to maintain the trigraph composition of the pseudowords equivalent to that of the words. As a result, the average digraph frequency of the pseudowords was very similar to that of the words, but there was a large difference in average trigraph frequency between these two categories of stimuli. Examples of the pseudowords used in the experiment are ber, bret, stred and bertse for the 1H category (left-hand strings), and voe, buth, rohtu and shrdne for the 2H category (left-starting strings).

Finally, a set of "nonwords" was constructed which preserved neither the digraph nor the trigraph composition of the words. The nonwords were made by recombining the letters found in the words of the same length, motor composition (1H versus 2H), and starting hand (left versus right). Except for the restrictions inherent to the experiment, this recombination process was random. As a result, the nonwords had a much lower average digraph and trigraph frequency than the other two types of stimuli. Examples of the nonwords used in the experiment are bsd, tsge, dsrte and efedet for the 1H category (left-hand strings), and fuv, tken, gubht and bysndi for the 2H category (left-starting strings).

In general, there were 16 different stimuli for each combination of the length, orthographic composition, motor composition and starting hand factors. Some of the length 6 conditions were under-represented because not enough words could be found which satisfied all the requirements of the experiment. The method used to generate the nonsense strings guaranteed that the same imbalance would be present among the pseudowords and the nonwords as well. Strings of length 2 were also used in the experiment. These strings consisted of digraphs of varying frequency. Since the pseudoword-nonword distinction, as it was defined previously, does not apply to strings of length 2, the results obtained with these strings will not be considered here.

Design. Each subject was tested under all the stimulus conditions involved in the experiment. For most conditions, there were 12 test trials on which the subject had to type the string presented, and 4 catch trials on which no response was required from the subject. The conditions in which fewer than 16 different strings were available allowed for fewer catch trials so that, over all stimulus conditions, 23% of the trials were catch trials. The allocation of the strings to catch and test trials varied across subjects, and the number of times

each string was used as a test stimulus and as a catch stimulus was proportionally the same for both skill groups.

The experiment required four sessions per subject, each session being held on a separate day and lasting approximately 45 min. The sessions involved three blocks of trials each: one block for the words, one for the pseudowords and one for the nonwords. The order of the blocks varied over sessions and over subjects, in a balanced way across skill groups. The motor composition of the strings, the starting hand, and the string length varied randomly within each block.

The first session was considered a practice session, each block containing 40 trials. The stimuli used for practice were different from those used on experimental trials, but they were constructed following the same principles. In addition, the typing speed of the subject was estimated at the beginning of the first session from a sample of about 1000 keystrokes of normal, continuous transcription typing. For the last three sessions each block contained about 115 trials, the first 12 being considered practice. The trials on which the subject made an error were repeated at the end of the block in which the error had occurred.

Procedure. The experiment was performed on a Hazeltine 1500 terminal. Each trial was announced by the terminal sounding a beep. Two hundred msec after the beep, a letter string was displayed for one sec in the center of the screen. Following the disappearance of the string, there was a period of 1.7 sec without any event before the subjected heard a short burst of white noise. This first burst of white noise was followed 700 msec later by a second burst of white noise which was followed another 700 msec later by a tone. Catch trials were signaled to the subject by a low tone (150 Hz), whereas a high tone (500 Hz) informed the subject to type the stimulus string "as fast and accurately as possible." The characters typed by the subject on test trials were recorded but they were not displayed on the terminal screen. A new trial was initiated 3 sec after the completion of the subject's last keystroke, or after the low tone when no response was required.

## Results of the Skilled Group

The subjects' means were submitted to two separate analyses of variance: one bearing on the latency data and the other on the average interstroke intervals. The trials with a latency longer than 3 sec and those in which one or more interstroke intervals were longer than 2 sec were eliminated prior to analysis. Note that the same cutoff points were used for all the experiments reported herein. They resulted in the loss of 0.2% of the data collected with skilled subjects in the present experiment.

Orthographic composition. With respect to the orthographic effects, the results are exactly opposite to those obtained by Sternberg, Knoll, and Wright (1978) with typists of comparable ability. As is shown in Figure 4, the performance obtained with the words and the

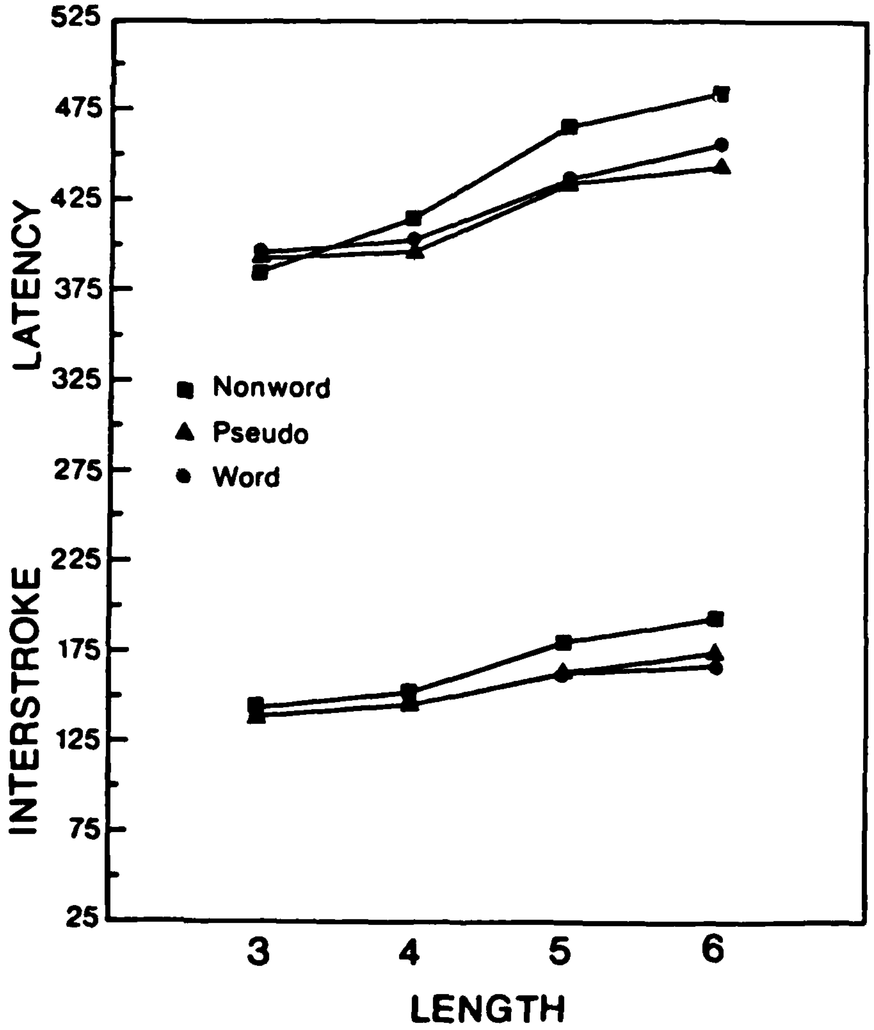


**Figure 4.** Latencies and average interstroke intervals for the words, pseudowords and nonwords composed of 3 to 6 letters. Results of skilled typists in Experiment 1.

pseudowords was almost identical, at least up to length 5. By contrast, the curves obtained with nonwords diverge from the others much earlier.

At the statistical level, the overall orthographic effect on the interstroke intervals was found to be significant, $F(2,6) = 12.6$, $p < .01$. Further interstroke interval comparisons showed a non-significant difference between the words and the pseudowords ($F < 1$), but a significant difference between the nonwords and the other two stimulus categories, $F(1,6) = 24.6$, $p < .01$. The overall length effect was significant, $F(3,9) = 37.8$, $p < .001$; and so was the length X orthographic composition interaction, $F(6,18) = 2.91$, $p < .05$.

Despite the general similarity between the latency results and the interstroke intervals, none of the above-mentioned effects or interactions reached the .05 level of statistical significance in the analysis performed on the latency data. It must be remembered that each trial in the experiment contributes to many interstroke intervals, but only one latency observation. This probably accounts for the difference in power between the two analyses.

Finally, it is worth mentioning that the error rates paralleled the temporal data, with a non-significant 1% difference between the words and the pseudowords ($F < 1$) and a significant 4% difference between these two categories and the nonwords, $F(1,6) = 6.92$, $p < .05$. While the difference between the words and the pseudowords remained smaller than 2% at all string lengths, there was a tendency for the difference between the nonwords and the other two categories to increase with the length of the strings. As a result, the overall length X orthographic composition interaction was significant, $F(6,18) = 3.51$, $p < .05$.

Motor composition. On average, the typing of 2H sequences took 39 msec longer to initiate then did the 1H sequences, $F(1,3) = 4.41$, $p < .25$. However, the average interstroke intervals were 59 msec shorter for the 2H sequences, $F(1,3) = 280$, $p < .001$. These differences were fairly constant across the various orthographic categories. The F ratio for the interaction was smaller than 1 in the interstroke data, and it was 1.22 ( $p < .50$) in the latency data.

As shown in Figure 5, the average interstroke intervals obtained with 1H and 2H sequences increased by about the same amount with increasing string length. A trend analysis, performed on the interstroke intervals, showed the linear component to be significant for both the 1H and the 2H sequences, with slopes of 5.9 and 7.2 msec/keystroke, respectively. However, both curves have significant, or marginally significant residual components. Seventy-five percent of the variance associated with the length X motor composition interaction was attributable to these higher-order components. The interaction itself was not quite significant, $F(3,9) = 3.17$, $p < .10$. In the latency data, the slopes of the 1H and 2H sequences were estimated at 11.4 and 14.1 msec/keystroke, respectively. The F ratio for the length X motor composition interaction was of 2.16, $p < .25$.

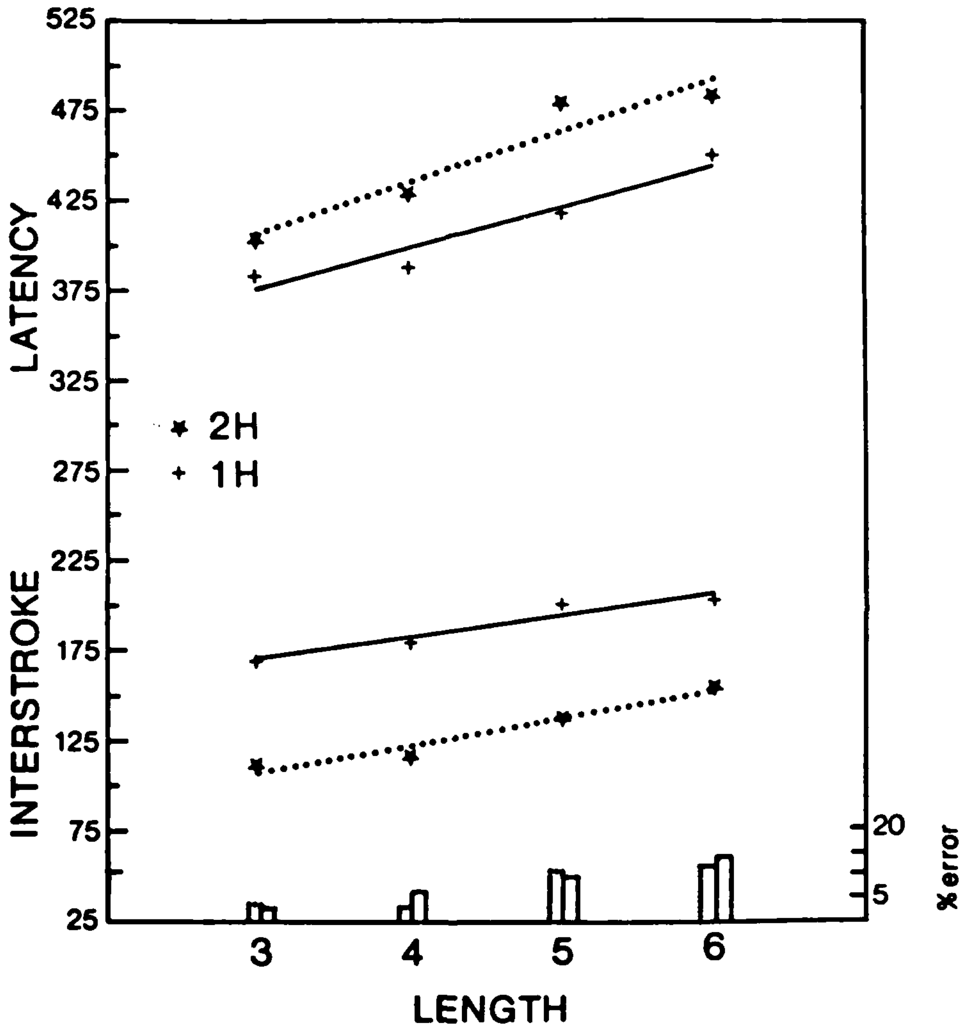


Figure 5. Latencies and average interstroke intervals for the 1H and 2H sequences of 3 to 6 keystrokes, along with the best fitting linear trend. The bar histograms represent the error rates for the same conditions. Results of skilled typists in Experiment 1.

The error rates, presented at the bottom of Figure 2 exhibit a monotonic increase with string length, $F(3,9) = 11.9$, $p < .01$, and a non-significant overall advantage in favor of the 2H sequences, $F(1,3) = 4.52$, $p < .25$. As in the interstroke data, there was a marginally significant interaction between the length and the motor composition of the sequences, $F(3,9) = 3.36$, $p < .10$, but no higher-order interaction with the orthographic composition of the strings, $F < 1$. In short, there was no evidence of speed-accuracy trade-off in the performance of the skilled subjects.

## Discussion

With respect to the motor composition effects, the results just reported are in agreement with those obtained by Sternberg, Monsell, Knoll and Wright. Sternberg et al. also found the advantage in interstroke interval favoring the 2H sequences to be independent of the length of the sequences. However the length effects they obtained with strings of 2 to 5 letters were strictly linear.

Following the logic of stage additivity (Sternberg, 1969), Sternberg et al. proposed a two-stage model to account for these results. According to their model, a motor representation of the stimulus string is established prior to the start of the typing response. This representation consists in a set of motor routines, each routine specifying the motor commands needed to execute a keystroke, or perhaps a short sequence of keystrokes. The motor routines are stored in an output buffer until the *go* signal is given. The typing of the stimulus string is achieved through the repeated operation of the following two processes. One process consists in searching the output buffer for the routine needed for the upcoming keystroke(s). The time required by the search stage is assumed to depend on the number of routines in the buffer which is, in turn, a function of the length of the stimulus string. The nature of the motor transition between two successive keystrokes (1H versus 2H) is assumed to affect the next stage of processing which consists in "unpacking" the routine and executing the motor commands.

This model does not easily account for the lexical-orthographic effects obtained later by Sternberg, Knoll and Wright. Since the motor routines, which are the basic units in the model, correspond to single keystrokes or short sequences of keystrokes, it seems that performance should be more sensitive to variations in the frequency composition of the letter strings than to differences in their lexical nature. Sternberg et al. found the opposite. Their results showed a lexical category effect, but no digraph frequency effect. However, the two factors could easily have been confounded in Sternberg et al.'s experiment. They report no effort to maintain the digraph frequency of the words and nonsense strings equivalent. The results obtained here indicate that words and nonsense strings yield identical performance when such a control is enforced.

If the words and the pseudowords used in this experiment had a similar average digraph frequency, the words had an increasingly large frequency advantage at the trigraph and higher-order n-graph levels. The fact that these differences were not reflected in performance suggests that these higher levels of structure contribute very little to skilled typing, and that digraphs may be the largest units from which the motor component is derived.

With such a constraint on unit size, Sternberg et al.'s model can easily accomodate the current results. The presence of an interaction between the length and the orthographic composition of the strings suggests that these two variables influence the same level of processing; namely, the search stage. In the model, the search is assumed to operate on a buffer containing the motor routines. If each routine specified two keystrokes, the same number of routines will be needed to represent the words and the pseudowords used in the experiment, since these two stimulus categories had the same digraph composition. By contrast, the nonwords used in the experiment were made of much lower frequency digraphs, some of which never actually occur in English. For illegal digraphs, there cannot be any predefined motor routine in long term memory, and the probability that such engrams exist for infrequent digraph is also low. Consequently, the nonwords would have to be decomposed into smaller units, with some routines corresponding to single keystrokes. The greater number of routines in the buffer would be responsible for the longer search times obtained with nonwords.

This revised model is somewhat unsatisfactory in that it still leaves too many aspects of the typing process ill-defined. However, it does provide a very economical account of skilled performance, with which to contrast the properties of novice typing.

## Results of the Novice Group

Forty-one trials (0.7% of the data) were eliminated prior to analysis because their latency was longer than 3 sec or because some of the interstroke intervals exceeded 2 sec.

*Orthographic composition*. The lexical-orthographic composition of the strings had a significant effect on both the latency period, $F(2,14) = 6.41$, $p < .05$, and the average interstroke intervals, $F(2,14) = 7.64$, $p < .01$. The interaction between the length and the orthographic composition of the strings was also significant in both the latency data, $F(6,42) = 5.33$, $p < .001$, and the interstroke data, $F(6,42) = 4.21$, $p < .01$. As shown in Figure 6, the nonwords produced much greater length effects than the words. Remember that a similar but weaker trend was present in the results of the skilled typists. What is particular to novice performance is that the pseudowords also produced greater length effects than the words. This is especially evident in the latency data, $F(3,42) = 3.61$, $p < .05$, but the simple interaction was also significant in the interstroke data, $F(3,42) = 2.98$, $p < .05$. The overall difference between the words and the pseudowords was not significant in either the interstroke ($F < 1$) or the latency data ($F(1,14) = 3.19$, $p < .10$).

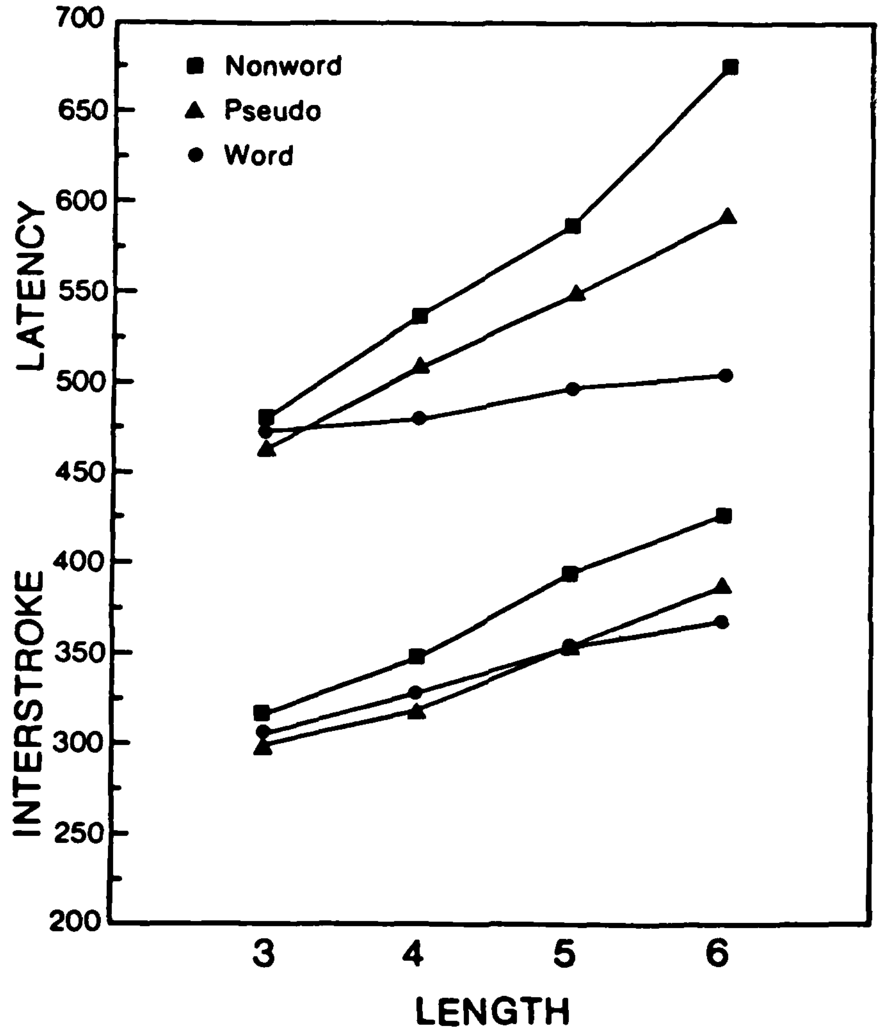


Figure 6. Latencies and average interstroke intervals for the words, pseudowords and nonwords composed of 3 to 6 letters. Results of novice typists in Experiment 1.

By contrast with the temporal data, the error rates showed a significant difference between the words (6.0% error) and pseudowords (9.7% error), $F(1,14) = 6.82$, $p < .05$. This result suggests that the fast typing rate obtained with the pseudowords was achieved at the cost of some accuracy. The nonwords produced significantly more errors (13.4%) than the other two stimulus categories, $F(1,14) = 18.9$, $p < .001$. As a result the overall lexical-orthographic effect was significant. The error rates showed the same patterns of interactions described previously for the temporal data.

Motor composition. Figure 7 shows the length effects on the sequences of different motor composition. In the latency data, the 1H sequences had a significant advantage ($F(1,7) = 8.15$, $p < .05$) over the 2H sequences. The advantage appeared at all string lengths. The slopes estimated for the 1H and 2H sequences were of 20.2 and 19.7 msec/keystroke respectively. The F ratio for the length X motor composition interaction was less than 1. By contrast, there was a clear interaction in the interstroke results, $F(3,21) = 3.46$, $p < .05$. Of the variance associated with this interaction, 96% was attributable to the difference in slope between the 1H sequences (11.6 msec/keystroke) and the 2H sequences (17.9 msec/keystroke).

Neither the latency nor the interstroke results showed any interaction between the orthographic and motor composition factors (both $F < 1$). The 3-way interaction, also involving the length of the strings, yielded an F ratio of 0.43 in the latency data. In the interstroke data, there was a tendency for the 1H and 2H functions to converge at a faster rate when nonwords were used as stimuli. The difference in slope between 1H and the 2H nonwords was of 9 msec, the difference being of 4 msec for the words. Despite this tendency, the overall 3-way interaction was not significant, $F(6,42) = 1.46$, $p < .25$.

There was no difference in error rate between the 1H and the 2H sequences, nor was there any interaction between the length and the motor composition of the sequences (both $F < 1$). However, the 3-way interaction, also involving the orthographic composition of the strings, was significant, $F(6,42) = 4.63$, $p < .01$.

## Discussion

Neither Sternberg et al.'s original model, nor the revised version discussed previously, can easily be extended to account for the results of the novice subjects. The independence of the search and execution stages was the cornerstone of the model proposed to explain skilled performance. The presence of a length by motor composition interaction in the interstroke results obtained with the novices suggests, on the contrary, that a single stage of processing may be involved. So, when they are interpreted following the logic of stage additivity, the results of the novice and skilled subjects lead to view the skill acquisition process as one through which the various operations involved in typing become increasingly separate in time and resources.

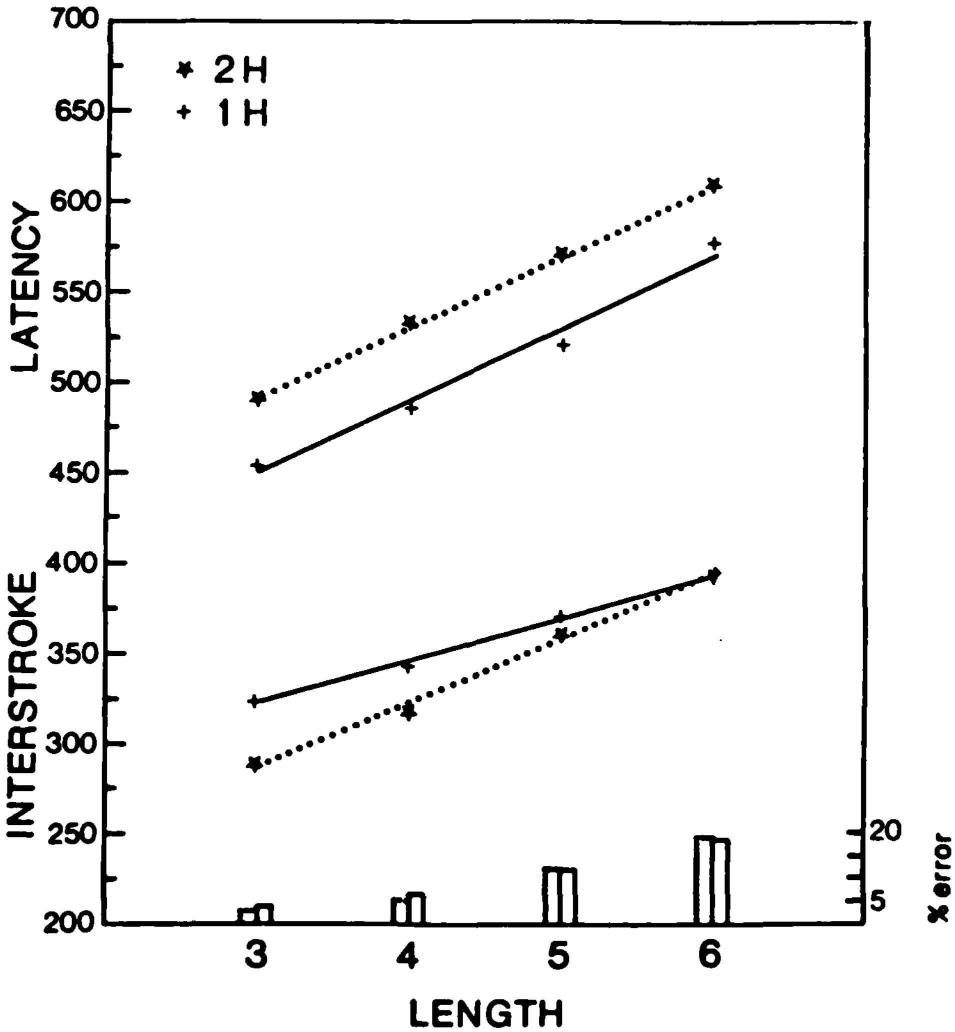


Figure 7. Latencies and average interstroke intervals for the 1H and 2H sequences of 3 to 6 keystrokes, along with the best fitting linear trend. The bar histograms represent the error rates for the same conditions. Results of novice typists in Experiment 1.

I wish to propose the totally different if not opposite view that the processes involved in typing can overlap in time, and that the amount of temporal overlaps between the organization and the execution stages increases with the skill level of the subjects. However, before developing this view, I will consider an alternative explanation for the results. This explanation consists of attributing the differences between skilled and novice performance to a difference in the scope of the motor program which is established prior to the onset of the typing response.

Sternberg et al.'s model is a complete pre-programming model in the sense that the access to the motor engrams corresponding to the letters or digraphs composing a string is assumed to have occurred prior to the onset of the typing response. If indeed skilled typists can pre-program sequences of up to six keystrokes, novice subjects may not be able to do so. The necessity to do some on-line programming while typing the sequence could be at the origin of the length X motor composition interaction found in the interstroke data of the novice subjects. One need only assume that sequences of keystrokes which require hand alternations are more complex to program than 1H sequences, an assumption which is consistent with the longer latencies usually observed with 2H sequences. Because of their inability to fully pre-program the sequences, novice typists would have to maintain the orthographic representation of the string active during the execution of the typing sequence. This would explain why variations in the lexical-orthographic coherence of the strings had a greater impact on novice than skilled performance.

There are several difficulties with the notion that it is the extent of pre-programming which distinguishes skilled from novice performance. First, one would expect the length and the motor composition of the strings to have over-additive effects on the latency period in case of complete pre-programming. This prediction follows from the fact that the number of hand changes which must be pre-programmed increased with the length of the strings combined with the assumption made earlier that interkeystroke transitions which involve a hand change require more programming time than transitions which involve fingers of one hand. There was indeed a small difference in slope between the 1H and the 2H sequences in the latency data of the skilled subjects, but the interaction was far from significant.

The preceding argument is not in itself sufficient to reject the scope of programming explanation. It is possible that the latency period does not reflect the entire programming time. Some amount of programming could have occurred prior to the <u>go</u> signal, thereby preventing a length X motor composition interaction from showing up in the latency results of the skilled subjects. Furthermore, as Sanders (1980) has argued, it is quite difficult to interpret the absence of an interaction when the factors involved do not produce strong main effects. Remember that the motor composition of the strings did not produce a significant effect on the latencies of the skilled typists. The following argument is less vulnerable.

Serial position effects, like those shown in Figure 5 and 6, are a typical finding in discontinuous typing experiments. Ostry (1980) has argued that the rise in the interstroke intervals toward the middle of a typing sequence reflects that time needed to program the latter part of the sequence. By contrast, the keystrokes occurring in last position presumably benefit from the fact that there are no further keystrokes to program, whereas those occurring in second position benefit from the fact that they have been programmed during the latency period. So, if the convergence of the 1H and the 2H sequences, which characterized the average interstroke intervals obtained with novice subjects, was due to the increasing need for on-line programming with longer strings, then this convergence should be much more pronounced at the peak of the serial position curves than in second and last positions.

The serial position effects presented in Figure 8 are those obtained with novice subjects. A comparison of the left and right panels at position 2 shows a clear tendency for the differences between the 1H and the 2H sequences to decrease as the length of the strings increase. Furthermore, this tendency is about as strong as the one found at the peak of the serial position curves and in last position. Since the number of interstroke intervals varies with the length of the strings, it is difficult to directly test for the presence or absence of an interaction among the length, the motor composition of the sequences and the keystroke position. However, none of the 2-way interactions involving the motor composition of the sequences and the keystroke position was statistically significant (all $p < .10$) in any of the analyses performed on the strings of each length. The main position effect was significant ( $p < .05$) for all strings except those of length 4 ($F < 1$).

Finally, if the skilled subjects were planning further ahead than the novice subjects, then the peaks of the serial position curves should have occurred in later positions, with no peaks in case of complete pre-programming. The serial position curves obtained with the skilled typists are presented in Figure 9. Except for the 4-letter strings ($F < 1$), all the curves show significant position effects. Furthermore, the 1H curves peak in the same position as the curves obtained with novice subjects. There is a tendency for the 2H curves to peak later than the 1H curves. However, this tendency was not strong enough to produce a significant motor composition X position interaction, even in the case of 6-letter strings: $F(4,12) = 2.60$, $p < .10$.

In sum, the difference between the two skill groups is not in the presence versus absence of serial position effects, nor even in the shape of the serial position curves. The difference is in the distance separating the curves obtained with various sequence lengths, and in their steepness. So, I wish to propose that what distinguishes skilled from novice typing is the rate at which the various letters in a string are transformed into keystrokes instead of the number of letters which can be pre-programmed.

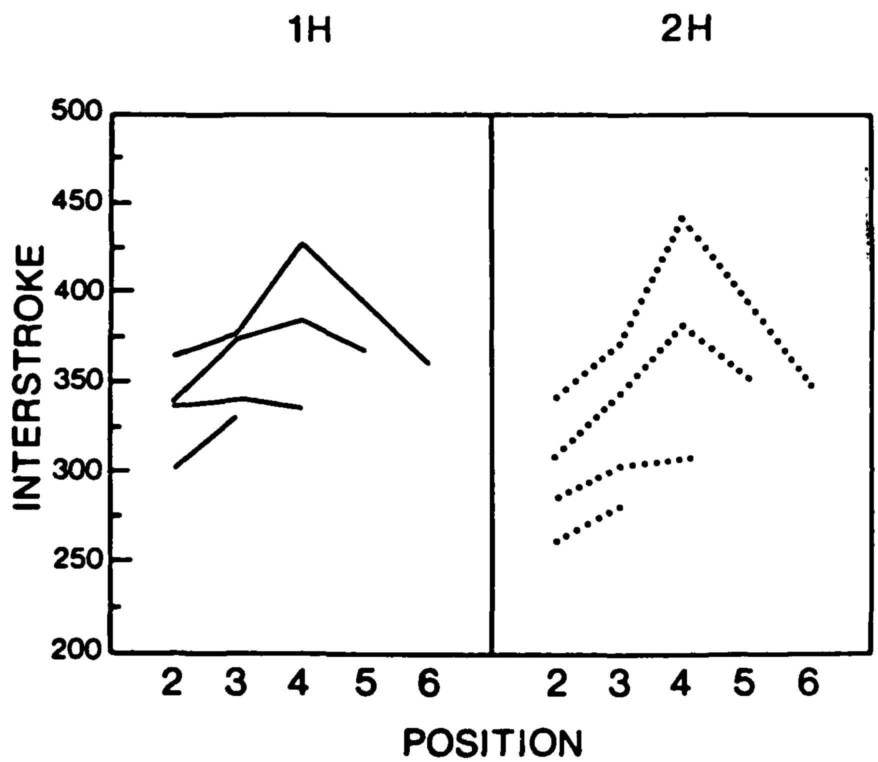


Figure 8. Interstroke intervals for each position in 1H and 2H sequences of 3 to 6 keystrokes. Results of novice typists in Experiment 1.

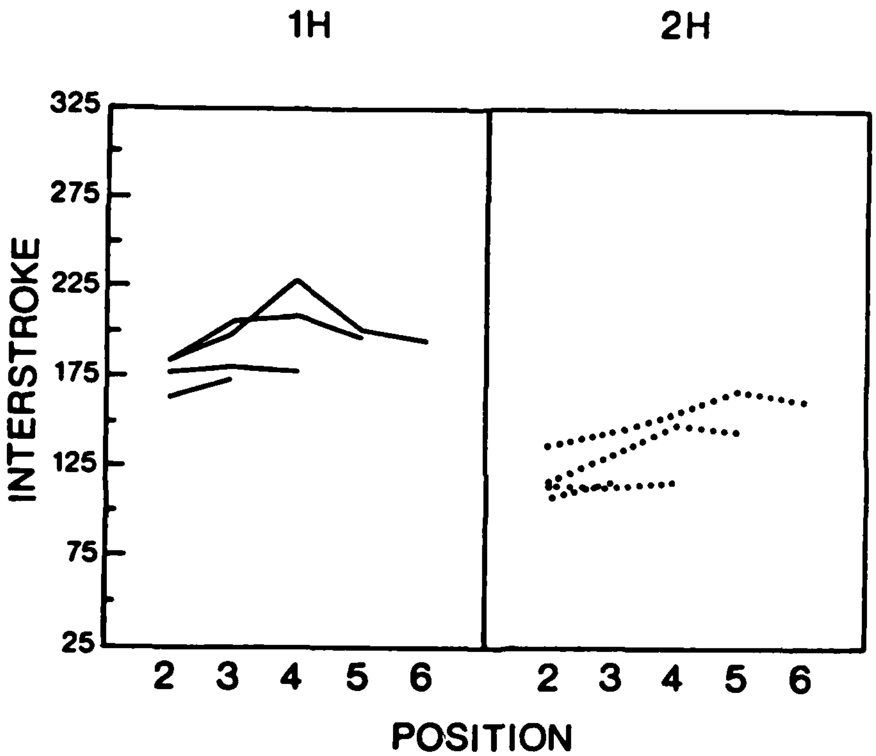


Figure 9. Interstroke intervals for each position in 1H and 2H sequences of 3 to 6 keystrokes. Results of skilled typists in Experiment 1.

According to this view, the organization of the typing response starts in a search of the orthographic representation of the strings. The search is not viewed as a linear scan operating on the content of some buffer, but rather as an activation process of the type which is usually assumed to operate on a verbal representation. The minimal purpose of the search is to find which letter to type next. The search may also serve to determine the location of the keys associated with the letters and to choose the appropriate effectors: hand and finger. Finally it is also possible that some motor engrams corresponding to sequences of letters are also found. This possibility will be discussed in more detail later.

The length effects, the orthographic effects, and the serial position effects are all thought to originate at this very high level of processing. Indeed it is presumably easier to remember the identity and especially the order of the letters when the strings form words than when they do not. Additional letters also increase the burden on memory, especially when the strings have little orthographic coherence. Finally, the position of the letters in the strings is also thought to affect their activation level. The model developed by Ratcliff (1978) shows how an activation-based memory access mechanism can produce serial position effects along with linear length effects.

After the spatio-temporal trajectory needed to reach the keys has been specified, the movements are executed. So the execution of a given keystroke must await the completion of the higher levels of processing. With increasing skill, however, it may become possible to search for the location of a key and to specify the spatio-temporal trajectory needed while executing a previous keystroke. In such a case, the interstroke intervals will reflect the temporal properties of the latter, execution stage, but they will not be influenced so much by the factors affecting the higher levels of processing. Within this framework, the smaller length, orthographic and serial position effects obtained with skilled typists suggest that the preparation for future keystrokes was almost completed during the execution of previous ones.

Not only can there be overlap between the organization and the execution of the typing response, but there can also be temporal overlap within the execution level itself. In conditions where the higher-level processes are faster than the actual execution times, the movements involved in typing a letter can be initiated prior to the completion of the previous keystroke. This overlap in movement does not result in a pure gain of time however. The presence of overlap in movement will generate mechanical constraints on the fingers involved, except in the very rare occasions when the fingers are moving in the same direction. Such constraints will tend to be stronger in 1H than in 2H sequences. Indeed, the amount of work done by the fingers in typing 2H sequences is reduced by half, compared to the amount of work done by the same fingers in typing 1H sequences. It is this difference in mechanical constraints which presumably accounts for the difference in the average interstroke intervals obtained with 1H and 2H sequences.

The amount of time gained in typing 2H sequences also depends on the speed of the higher-level processes. With longer preparatory times, there will be less overlap in movements and consequently less difference in mechanical constraints between 1H and 2H sequences. Such an account is consistent with the length X motor composition interaction which was present in the interstroke data obtained with novice subjects. This account also leads to expect interactions involving the orthographic composition of the strings. Remember that the 3-way interaction among the length, the orthographic and the motor composition of the sequences failed to be significant, even with novice typists as subjects. However, such an interaction was present in the error data of the novice subjects. The practice obtained by repeating the trials on which errors had occurred may have prevented the interaction from being fully manifest in the interstroke results. The next experiment shows that an interaction among the interstroke intervals can be produced by degrading further the orthographic coherence of the nonsense strings and by putting more emphasis on the accuracy of the typing response.

The latency results did not exhibit the same length X motor composition interaction, which characterizes the interstroke intervals obtained with novice subjects. So, how can the view of typing which was proposed to account for the interstroke results also account for the latency data? There is one seemingly trivial difference between the latency period and the following interstroke intervals which is of critical importance in understanding the difference in results; namely, the fact that the latency period is not bounded by two keystrokes. Since the latency period extends from the <u>go</u> signal to the first keystroke, it can include whatever time is needed to reach and strike the first key. It can also include whatever organization time is needed at the start of the typing response. As was argued before, the interstroke intervals may not reflect much of the organization time needed for a keystroke if the planning is done during the execution of previous keystrokes. In cases where there is overlap in the movements leading to two successive keystrokes, the interstroke interval will even be shorter than the actual time needed for the execution of the second keystroke. In short, the interstroke intervals reflect a variable amount of organization and execution time depending on the nature of the stimulus and on the skill level of the subjects. By contrast, the organization and execution of the first keystroke, cannot overlap with the execution of previous keystrokes because there is no such previous keystroke. This may explain why the factors which are thought to affect the organization and execution times produced additive effects on the latencies. This may also explain why the latency results of the skilled and novice subjects were more similar then their interstroke results.

There is one final aspect of the results which needs to be considered; namely, the tendency for the 2H sequences to produce longer latencies than 1H sequences. This is a puzzling result considering that the difference in interstroke interval was in the opposite direction. The reason for this reversal is perhaps related to the freedom of movement involved in typing 1H and 2H sequences. I have argued earlier that the movements were less constrained in the case of 2H sequences, thereby

allowing for shorter execution times than in the case of 1H sequences. The greater freedom of movement which characterizes 2H sequences could possibly have the opposite effect on the time needed to plan the movements. Keystroke transitions which involve a hand change may require more organization time because there is a greater number of possible spatio-temporal trajectories to consider than in the case of the more constrained 1H transitions. Alternatively, the organization of 2H transitions may be more complex because of the necessity to coordinate a greater number of dynamic links. The important point is that the interstroke intervals would not reflect such a difference in organization time if the planning of successive keystrokes (or interkeystroke transitions) occurred during the execution of previous ones. Since there is no keystroke before the first one, the latency period could reflect the difference in organization time between 1H and 2H sequences, provided that the planning done during the latency period extends up to the second keystroke.

The preceding argument concerning the reversal of the latency and the interstroke results remains quite speculative, but it follows naturally from a view of typing which allows the organization and execution of successive keystrokes to overlap. By contrast, a model like the one proposed by Sternberg et al., in which there is a strict seriality of processing all through the typing sequence, is hardly compatible with the finding that 2H sequences produce longer latencies but shorter interstroke intervals than 1H sequences.

## Experiment 2

In explaining the results of the previous experiment, I have argued that the movements leading to successive keystrokes can overlap in time. However, the results themselves did not provide any evidence of the presence of overlap in movement. In this experiment, I analyze the conditions which give rise to movement overlap in skilled and novice typing.

### Method

The method adopted is based on an extreme form of response-response incompatibility; namely, the fact that the same effector cannot move in two different directions at the same time. For instance, in typing the digraph tr with the standard method, the left index, which is responsible for typing both keys, cannot move toward the r before the t is typed. By contrast, in typing the digraph dr, two different fingers are used, so it is physically possible for the index to move toward the r key while the middle finger is still reaching for the d key. By comparing the interstroke intervals obtained in situation where overlap is possible, with situations where overlap is impossible, one can determine if overlap in movement contributes to the typing speed.

Subjects. The subjects participating in this experiment were different from those used in the previous experiment. All ten subjects were right-handed. The average typing speed of the five subjects in the

skilled group was 60 words/min, compared with 23 words/min for the novice group.

Stimuli. The stimuli were letter strings composed of 3 to 5 letters. One half of the stimulus strings were typed by the fingers of one hand, the other half involved both hands.

The 1H strings were constructed in such a way that, in each string, two of the letters were typed by one finger, none of the other fingers being used for more than one keystroke. In half of these strings, the repeated finger typed two successive letters. In this condition, called the 1F condition, it is the second keystroke executed by the repeated finger which is of critical interest because the interstroke interval precludes overlap in finger movement. The position where the finger repetition occurred varied across strings: In 3-letter strings, the first two letters were typed by the same finger so the critical keystroke was always in position 2. With strings of length 4, the critical keystroke was either in position 2 or 3; with strings of length 5, it occurred in position 2, 3, or 4. There was an equal number of strings for each of these positions so that, in the ensemble, there was an increasing number of strings of length 3, 4, and 5.

The other half of the 1H strings were such that the two keystrokes produced by the same finger were separated by one intervening keystroke. This condition will be labeled the 2F condition because the finger responsible for the critical intervening keystroke was different from the finger used in typing the preceding key. Therefore the interstroke interval could reflect some overlap in movement. Different strings were constructed so that, over all strings, the critical keystroke occurred equally often in every possible position between the first and the last keystroke.

By contrast with the 2H strings used in the previous experiment, the ones used here involved only one hand alternation (two hand changes), so that all the keys but one were typed by the same hand. Half of the 2H strings were equivalent to the 2F strings just described, except that the critical intervening keystroke was produced by a finger of the alternate hand. This finger was not homologous to any of the other fingers involved in typing the string. Since the critical keystroke was the only one executed by the alternate hand, this condition allowed for overlap in both hand and finger movement.

The same was true of the other set of 2H strings. However, the keystrokes immediately surrounding the critical one were executed by different fingers. The finger used in typing the critical keystroke was homologous to the one preceding or following it, depending on the string. This set of strings was introduced in the experiment mostly to balance the number of 1H and 2H strings. The results obtained with this set of stimuli will not be reviewed here, so that the 2H label will be used only to refer to the other set of two-hands strings.

Unfortunately, I could not find enough words which satisfied the constraints just described concerning the motor composition of the stimuli. So, all the stimuli were nonsense strings. Half of them were composed of relatively high-frequency digraphs. These stimulus strings will be referred to as "pseudowords" for mnemonic purposes. The set of pseudowords was evenly split over both hands, half of the strings starting with a left-hand key and the other half starting with a right-hand key. No letter was allowed to appear more than once within a given string, and the letters c, x and z were eliminated altogether from the composition of the stimuli (as had been done for the previous experiment). However, since there are only two vowels under the left hand, it was impossible to eliminate the letter a and still obtain high-frequency strings. Instead, the letter q was eliminated from the construction of the pseudowords. With only one letter assigned to each little finger, the only fingers which could be used more than once within a given string were the index, the middle and the ring. Over all strings, these fingers were used about equally often to type the critical keystroke. Examples of 4-letter pseudowords used in the experiment are swad, fegs and doef for the 1F, 2F and 2H conditions respectively. In these examples, the critical keystroke occupies the second position.

In order to obtain a set of stimuli with less orthographic coherence than the pseudowords, but with a similar motor composition, each of the pseudowords was subjected to a mirror-image transformation. This transformation, which was also used by Ostry (1980), consists of replacing each letter in a string by the letter located in the equivalent position on the other half of the keyboard. Since there is no letter in the same position as a on the right half of the Sholes keyboard, the letter a was replaced by the letter p. The letter p was replaced by the letter q. The strings so produced had a much lower average digraph and trigraph frequency than the pseudowords from which they derived. They will be referred to as "nonwords". Here are the nonwords corresponding to the pseudowords mentioned previously: lopk, jihl and kwij.

Design and procedure. The pseudowords and the nonwords were presented in separate blocks throughout the experiment. The other factors involved in the composition of the stimuli varied randomly within each block. These factors were the length and the motor composition of the sequences, the position of the critical keystroke in the sequences, and the starting hand. These were ten pseudowords and ten nonwords for every possible combination of these factors. Of these ten strings, eight were used on test trials and two were used for catch trials, the subsets varying over the different subjects in a given skill group. Over all the subjects in a group, every string was presented four times as a test stimulus and one time as a catch stimulus. The stimuli used for practice were different from those used on experimental trials, but they were constructed following the same general principles.

The experiment required five sessions per subject, the sessions lasting less than one hour each and being held on separate days. As usual, the first session was for practice. It consisted of two blocks of 50 trials each: one block for the pseudowords and the other for

nonwords. There were 135 trials in each block of the following sessions, the first 15 trials in each block being considered practice. The order of trials within each block varied from subject to subject within a given skill group, and the order of the blocks varied both across subjects and across sessions. The same orders were used with both skill groups.

The procedure differed from the one used in the previous experiment on the following points. First, the subjects were asked to leave their fingers either on or slightly above the home row keys, depending on which position felt more natural, until the signal to respond was given. The purpose of this request was to insure some control on the position of the hands and fingers at the beginning of each trial, and to prevent the subjects from moving their fingers toward the keys to be struck prior to the signal. In order to motivate compliance with this request, the procedure followed on catch trials was modified. Rather than simply ignoring the letter string which had been presented and not responding, the subjects were asked to depress simultaneously the fingers of both hands on the keys located on home row, upon hearing the low tone. As in the previous experiment, test trials were signaled by a high tone. However, more emphasis was put on the accuracy of the typing response than in the previous experiment. The subjects were asked to "type the letter strings as fast as possible while keeping errors to a minimum." They were also explicitly told that their error rate should not exceed 10%.

## Results of the Skilled Group

As usual, trials with extra long latencies and/or interstroke intervals were rejected prior to analysis. This resulted in a loss of less than 1% of the data collected with the skilled subjects. By contrast with the previous experiment, only one interstroke interval was extracted from the remaining sequences: the interval preceding the critical keystroke. These intervals were averaged over all the positions occupied by the critical keystroke in the sequences of various lengths, and then submitted to two separate analyses of variance. One analysis was limited to the conditions involving fingers of the same hand; namely, the 1F and the 2F conditions. The other analysis was devoted to the conditions involving different fingers within (2F) and across hands (2H). The results of all three conditions are presented in Figure 7. It is the contrast between the 1F and the 2F results which is of primary interest here. The 2F and 2H conditions are analogous to those involved in the previous experiment. So, only the discrepancies in results or other important findings will be reviewed.

<u>The same-hand conditions</u>. As shown in the left panel of Figure 10, the typing of pseudowords did benefit from a finger change. There was an average difference of 41 msec in the interstroke intervals between the 1F and the 2F conditions, a difference which corresponds to a nontrivial gain in typing speed of 10 words/min. The right panel of Figure 7 shows that the mirror-image transformation of the stimuli greatly reduced the advantage of the 2F transitions. The overall difference

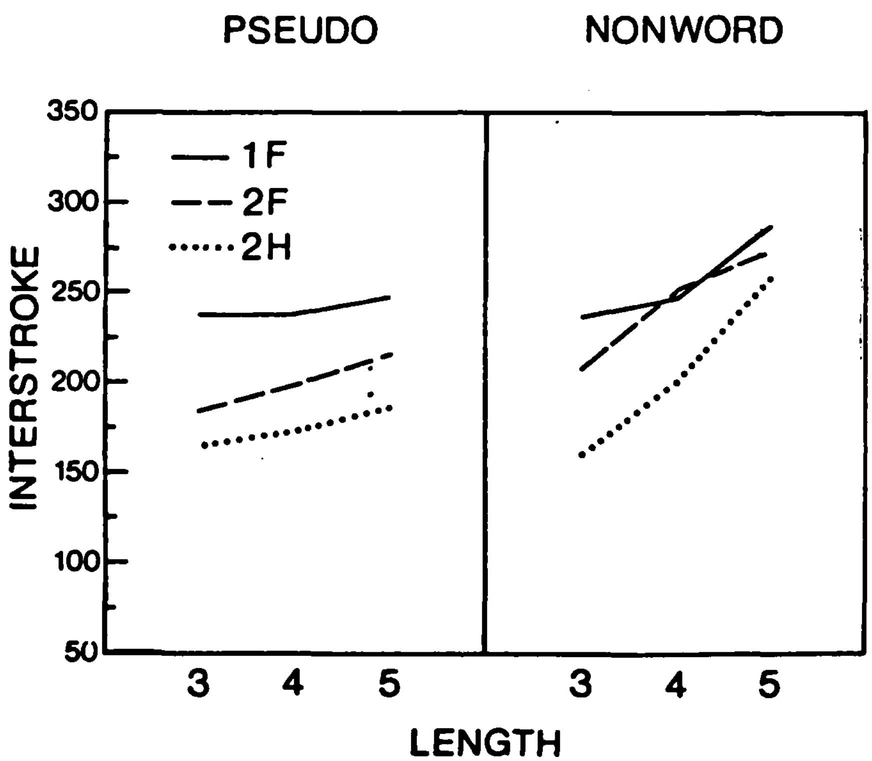


**Figure 10. Interstroke intervals preceding the critical keystroke for 1F, 2F, and 2H transitions embedded in sequences of 3 to 5 keystrokes. Results of skilled typists in Experiment 2.**

between the 1F and 2F conditions (motor composition effect) was significant, $F(1,4) = 8.38$, $p < .05$. However, the breakdown of the motor X orthographic composition interaction ($F(1,4) = 9.31$, $p < .05$) showed the difference to be significant only for the pseudowords.

The length effects obtained in the 1F and the 2F conditions were not sufficiently different to produce a significant length X motor composition interaction, $F(2,8) = 2.30$, $p < .25$. The 3-way interaction also involving the orthographic composition of the strings yielded a F ratio of 1.02, thereby indicating that the increase in length effects produced by the mirror-image transformation of the stimuli was of similar magnitude for the 1F and 2F conditions.

The different-fingers conditions. The results of the 2H condition show that, beyond the time gained from a finger change, there is additional time saved by a hand change. Indeed, the difference between the 2H and the 2F conditions was significant, $F(1,4) = 14.7$, $p < .05$. However, by contrast with the time gained from a finger change, the time gained from a hand change was not reduced by the mirror-image transformation of the stimuli. The motor X orthographic composition interaction was far from significant, $F(1,4) = 1.46$, $p < .50$. The 3-way interaction also involving the length of the sequences was marginally significant, $F(2,8) = 3.25$, $p < .10$. This interaction reflects a tendancy for the difference between the 2H and the 2F sequences to be greater among the nonwords, except at length 5. Such a tendency was absent from the results of the skilled subjects in Experiment 1, and it constitutes the only divergence between the two sets of results.

## Discussion

The results obtained with same-hand transitions provide a clear indication that overlap in finger movement contributes to skilled performance, and that the amount of overlap in movement is related to the orthographic composition of the typing material. The question raised by these results is: how is overlap in movement achieved? This question is closely related to the issue of the units which underlie typing performance.

The presence of overlap in movement is not incompatible with the notion that single keystrokes are the basic units of performance. I have argued earlier that a search of the orthographic representation of a string was necessary, even if it serves only to find the location of the key associated with each letter, and to choose the appropriate effector. As was shown by Rumelhart and Norman (1982), this information is sufficient to initiate the movements leading to any single keystroke. In the framework discussed here, the initiation of a given keystroke would therefore coincide with the completion of the search process. Overlap in movement would occur when the search required for the initiation of one keystroke takes less time than the execution of the previous keystroke.

If the view just summarized allows overlap in movement, it does not allow performance to exhibit overlap in movement along with strong length effects. Indeed, the presence of overlap in movement is an indication that it is the physical execution of the keystrokes which limits performance, as measured in terms of interstroke intervals. So, factors which are assumed to influence higher-level processes, like the length of the strings, should have minimal impact on performance when there is overlap in movement.

The results do not unambiguously support this view. The mirror-image transformation of the same-hand strings did produce an increase in length effect, and this increase was accompanied by a reduction of the amount of time saved by a finger change. However, the 2F condition showed a significant length effect, even among the pseudowords where there was a large advantage favoring the 2F transitions over the 1F transitions. Of course, it is possible that the length effect obtained with pseudowords originated in a few trials where there was no overlap in movement. The results obtained in the 2H condition provide stronger evidence for the separability of the length effects from the effects due to effect or availability. Indeed, the mirror-image transformation of the 2H strings produced the usual increase in length effect but no reduction in the amount of time saved from a hand change.

The fact that there was no general relationship between the size of the length effects and the amount of time gained from effector availability suggests that there may be some predefined response procedures which directly specify the coordination of the movements involved in a sequence of keystrokes. In this case, the presence of overlap in movement would not depend so much on the completion of some high-level search process, but rather on the content of the motor engrams corresponding to various digraphs or trigraphs. The search for these response procedures could proceed synchronously or asynchronously with the execution of previous ones, thereby allowing for sizeable length effects in conjunction with overlap in movement.

One question raised by this view concerns the nature of the motor engrams. It has been suggested (Gentner, Note 1; Terzuolo & Viviani, 1980) that the motor program specifies the inter-completion time of successive keystrokes, rather than their initiation times or some other dimension of the movements involved. This suggestion is hardly consistent with the results reported here. The nonwords used in this experiment were made of very low frequency digraphs and higher-order n-graphs. Presumably, the response procedures for such sequences do not provide very efficient interstroke timing. This would explain why there was little difference between the 2F and the 1F transition among the nonwords. The problem is that, in typing the nonwords, the 2H transitions should have produced results similar to those obtained with the 2F transitions. The fact that there was a difference in interstroke intervals between these two conditions suggests that dimensions, other than the interstroke times, are specified in the response procedures.

The results of a high-speed videographic analysis of continuous typing suggest that response procedures for high versus low-frequency sequences may be basically different. Grudin and Larochelle (Note 2) have presented an example of one type of movement re-organization which was centered on the times at which the fingers are retracted from the keys after the execution of a keystroke. Grudin and Larochelle have shown that, in typing the high-frequency sequence ion, the retraction of the middle finger from the i is often delayed until after the execution of the o thereby facilitating the reaching motion of the ring finger toward the o and reducing the interstroke interval. A similar organization may not be present in typing low-frequency sequences. The resulting increase in the mechanical constraints on movement would produce an increase in interstroke intervals. Note that, since the frequence effects are mediated by the mechanical constraints operating on the fingers of the same hand, one would not expect the same effects on transitions which involve a hand change. This is exactly what the results of this experiment show.

If some pre-defined response procedures exist for certain sequences of keystrokes, they must have been acquired with extensive practice in typing. The preceding argument suggests that the differences between skilled and novice typists should be especially manifest in the case of 2F transitions.

### Results of the Novice Group

Exactly 1% of the trials were excluded from the analyses because of extra-long latency and/or interstroke intervals.

The same-hand conditions. As is shown in the left panel of Figure 11, there was little time gained from a finger change in typing the pseudowords. The simple motor composition effect was not significant ($F < 1$), nor was the length X motor composition interaction, $F(2,8) = 1.36$, $p < .50$. Even the 20 msec difference between the 1F and the 2F transitions which was obtained with the pseudowords of length 3 was insignificant, $F(1,8) = 2.05$, $p < .25$. The mirror-image transformation of the pseudowords produced a reversal in the overall difference between the 1F and the 2F conditions, $F(1,4) = 4.79$, $p < .10$. Among the nonwords, the 1F transitions had a marginally significant advantage over the 2F transitions, $F(1,4) = 4.64$, $p < .10$, but the simple length X motor composition was still not significant, $F(2,8) = 2.30$, $p < .25$. It is only at length 5 that the difference between the 1F and the 2F nonwords was statistically significant, $F(1,8) = 9.01$, $p < .05$.

Further analyses revealed that some artifact in the composition of the stimuli may have contributed to the reversal of the 1F and 2F conditions across orthographic categories. The differences between the 1F and 2F transitions were limited to the left-hand strings. Among the left-hand pseudowords, the 2F strings (and the critical digraphs) had a large frequency advantage over the 1F strings (and critical digraphs). Among the left-hand nonwords, it is the 1F condition which had the frequency advantage over the 2F condition. Note that this type of bias was

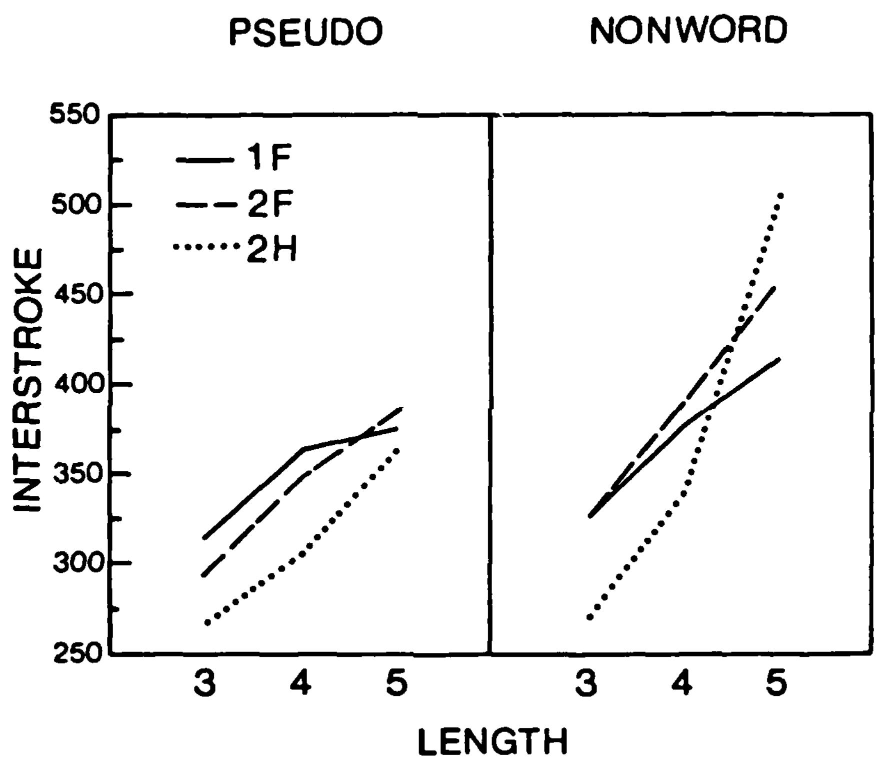


Figure 11. Interstroke intervals preceding the critical keystroke for 1F, 2F and 2H transitions embedded in sequences of 3 to 5 keystrokes. Results of novice typists in Experiment 2.

almost inevitable, given the disposition of the letters on the standard Sholes keyboard. A more complete discussion of the laterality effects which are induced by the configuration of the Sholes keyboard (when used with the standard method) can be found in Larochelle (1981).

The different-fingers conditions. If novice performance did not benefit much from a finger change, it did benefit from and hand change. In the typing of pseudowords, there was an average difference of 30 msec between the 2F and the 2H transitions, $F(1,4) = 19.1$, $p < .05$. This difference remained fairly constant at all string lengths, the F ratio for the simple interaction being smaller than 1. By contrast, there was a significant length X motor composition interaction among the nonwords, $F(2,8) = 13.49$, $p < .01$. This interaction is due to the reversal of the 2F and 2H conditions at length 5.

## Discussion

Among the results of the novice subjects it is the performance observed with the 5-letter nonwords which is perhaps the most intriguing. In this condition, the 2H transitions produced longer interstroke intervals than the 2F transitions. This result contrasts with the pattern of interstroke intervals obtained in all the other conditions (as well as with skilled typists), but it does correspond to the pattern of latencies usually observed. The times involved are also very close to those which characterize the latency period. For sequences in which the critical transition immediatley followed the first keystroke, there was an overall difference in the novice subjects' latencies of 46 msec between the 2H and 2F conditions. I have suggested earlier that this latency difference originates in the organization of the motor response. The fact that a difference, similar to the one exhibited by the latencies, was present among the interstroke intervals obtained with the 5-letter nonwords suggests that the same processes are still active during the execution of the typing sequence.

It is worth mentioning that there was also a tendency, in this experiment, for the 2F condition to produce longer latencies than the 1F condition. For instance, with novice typists, there was an overall difference in latency of 28 msec between the 2F and 1F condition when the critical transition immediately followed the first keystroke. The differences in interstroke intervals were usually in the opposite direction. So there seems to be a general complementarity of the latency and the interstroke data with respect to the freedom of movement involved in typing 2H, 2F and 1F transitions. If it is true that the latency period reflects more of the planning processes, then the results suggest that more organization time is needed when the constraints on movement are smaller.

## General Discussion

The experiments reported here provide a view of the interactions between globally defined levels of processing and of some of the changes which take place with skill. The results can be synthesized in the following way: As the constraints on movement decrease, from 1F to 2H transitions, the impact of the combined length and orthographic effects on the interstroke intervals increases. This type of under-additive interaction is an indication, but not a definite proof, of the presence of temporal overlap among the stages of processing involved (see Taylor, 1976; also McClelland, 1979). Since it is difficult to see how the length and orthographic effects could originate at the motor level, I have argued that these factors influence higher levels of processing involved in the preparation of the typing response. The suggestion that the organization and execution of successive keystrokes can overlap is not new. The same notion is present in the type of model proposed earlier by Shaffer (1976).

When viewed in this perspective, the results do guide our speculations about the acquisition of the typing skill. In order to type with the touch-typing method, one must first learn the position of the keys and the fingers which are associated with each key. This phase corresponds to what Rumelhart and Norman (1978) labeled the accretion stage. Until this knowledge is well established, typists would rely very heavily on the visual guidance and monitoring of the movements. At this stage, the preparation and the execution of successive keystrokes would proceed in a largely serial fashion, and the interstroke intervals could be even longer than the time needed to reach and depress the keys. As the basic knowledge gets established and the need for the monitoring of movements decreases, some resources can be allocated to the anticipation of future keystrokes. There is probably a long tuning phase during which the amount of overlap between the preparation and the execution of successive keystrokes gradually increases, until there can finally be overlap in the movements leading to successive keystrokes. At this stage, the interstroke intervals become gradually shorter than the actual movement times. The presence of overlap in movement raises some difficulties not previously encountered concerning the distribution of the work over the various dynamic links in the arms and hands. For instance, it may be efficient to move the hand as a whole in reaching for keys located on the same row, but when the keys are on different rows, it may become more efficient for the fingers to move separately. This type of problem could give rise to some re-organization of the movements involved in typing. The consequence of such re-organization, called restructuring by Rumelhart and Norman, would be the existence of specific response procedures for specific sequences of keystrokes.

Two final comments are in order. First, although I have distinguished three phases in the skill acquisition process, I do not view these phases as distinct time periods. Rather, I think of these phases as being tied to the frequency with which letters and sequences of letters are encountered. So, it would be possible for a relatively novice typist to have already elaborated a response procedure for the

very frequent sequence _the_, while still having difficulty in reaching for the letter _q_. In sum, I would not expect a longitudinal study of typing to show plateaus in global measures of performance.

The second comment concerns the scope of the response procedures. The results of the first experiment suggest that, if such pre-defined procedures contribute to skilled performance, they do not generally span more than two keystrokes. Remember that the skilled subjects of Experiment 1 produced identical performance with words and pseudowords, despite the differences in trigraph and higher-order n-graph frequency between these two stimulus categories. Such a result is hardly consistent with the theories of skilled typing which are based on the assumption that there are pre-defined response procedures corresponding to specific words (Leonard & Newman, 1964; Terzuolo & Viviani, 1980). It is true that the evidence supporting these theories does not come from global performance measures of the sort discussed here. What Terzuolo and Viviani found is that, despite variations in typing speed, the ratio of each interstroke interval to the total time needed to type a word remained fairly constant from one occasion to the next. It is not clear, however, if the phenomenon holds for many words, or if frequent words exhibit more regularity than infrequent ones (as they should). The view developed here is also consistent with some regularity in typing, the sources of regularity being the frequency composition of the strings, the nature of the motor transitions involved and the amount of movement overlap (which also restricts effector availability).

# KEYSTROKE TIMING IN TRANSCRIPTION TYPING [9]

Donald R. Gentner

Over the past few years, in collaboration with Jonathan Grudin, David Rumelhart, Donald Norman, and Serge Larochelle, I have been studying transcription typing in the laboratory. Typically, typists would be asked to transcribe normal English prose from typewritten copy. This corpus of naturalistic data, now totaling over half a million keystrokes, has been a rich vein of information on the development and performance of a highly practiced skilled action.

## Method

Typists. Most of this paper is based on data collected from six professional typists (Typists 1-6) who were normally employed as university secretaries. I refer to this group as the "expert typists." Their typing speeds on the experimental text ranged from 61 to 90 words per minute (assuming five keystrokes per word and with no adjustment for errors). A second group of four typists (Typists 7-10), the "super typists," were recruited from local businesses to study the upper end of typing skill. The super typists ranged from 85 to 112 words per minute on the experimental text. A third group of eight typists (Typists 21-28), the "student typists," were students in a beginning typing class from a local high school. The student typists were studied once a week in the third through eighth weeks of their typing class. The students did not type all the letters of the alphabet until the fourth week, so data from the third week were not included in these analyses. Their typing speeds on the experimental texts ranged from 13 words per minute for one student in the fourth week to 41 words per minute for another student in the eighth week. The data from the student typists were collected by Jonathan Grudin and kindly furnished by him.

Texts. The text typed by the expert and super typists was adapted from a Reader's Digest article on diets; it will be referred to as the "diet text." The diet text was approximately 12,000 characters long and was presented as double-spaced, typewritten copy. After a 10 minute warmup with another text, the typists were asked to transcribe the diet text at their normal, rapid rate, without correcting errors. The student typists were given several different texts to transcribe. The texts for the fourth and fifth weeks consisted of a number of unrelated prose paragraphs. The remaining texts for the student typists were

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The other people of the LNR Research Group made important contributions to the research reported in this paper. In addition to the authors of other papers in this report, Eileen Conway assisted with many of the experimental studies and data analysis.

prose passages adapted from Reader's Digest articles.

Apparatus. The typists worked at a high-quality electronic keyboard (Microswitch model 51SD12-4 with "tactile feel"). The keyboard layout was identical to that of the normal IBM Selectric typewriter (see KEYBOARD FIGURE). Keypresses and the corresponding times (with a resolution of 1 msec) were recorded by a microcomputer. The typed characters were displayed on a CRT in front of the typist. While the typists were transcribing the diet text, their finger movements were recorded on videotape using a Sony RSC 1050 Rotary Shutter Camera. A mirror mounted at the top of the keyboard at a 45-degree angle allowed simultaneous recording of two views of the typist's fingers (normal and parallel to the plane of the keyboard). The video fields, recorded every 16.7 msec, were serially numbered with an electronic video counter, and selected portions of the videotape were later analyzed, field-by-field, with a Sony SVM 1010 Video Motion Analyzer. Finger and hand coordinates were digitized from a video monitor by superimposing a joystick-controlled cursor on the video image. (Resolution with the cursor was 0.5 mm, with a reproducibility of about 1 mm.) These coordinates were used to calculate the successive positions of the fingers and hands in 3-dimensional space. Finger position was measured at the fingertip. Some analyses were based on the relative finger and hand movements. The hand position was measured at the skin above the point where the right index finger joins the palm (the metacarpophalangeal joint). The position of the fingertip was then determined relative to that point on the hand.

## Development of Typing Skill

A typical office typist, typing at 60 to 80 words per minute, is averaging five to seven keystrokes per second. How does a typist develop these rapid, accurate movements?

### The Range of Typists

Figure 12 illustrates the progression of interstroke interval distributions for a student typist at four and eight weeks, an expert typist, and a super typist. The most obvious change is a major increase in typing speed from 13 to 112 words per minute and a corresponding decrease in the median interstroke interval from 852 to 96 msec. In fact, when the distributions in Figure 12 are normalized by dividing the interstroke intervals by each typist's median interstroke interval, the four distributions are remarkably similar. But this similarity in the overall distributions masks major developmental differences. The interstroke intervals can be usefully grouped according to the class of digraph associated with them. Sequences of two keys typed by a single finger are called 1-finger digraphs (the typewriter keyboard is shown in KEYBOARD FIGURE); the 1-finger digraphs can be further subdivided into 1-finger doubles, such as dd, and 1-finger non-doubles, such as de. Sequences typed by two fingers on the same hand, such as se, are called 2-finger digraphs. Sequences typed by different hands, such as pe, are called 2-hand digraphs. When the distributions were separated into the

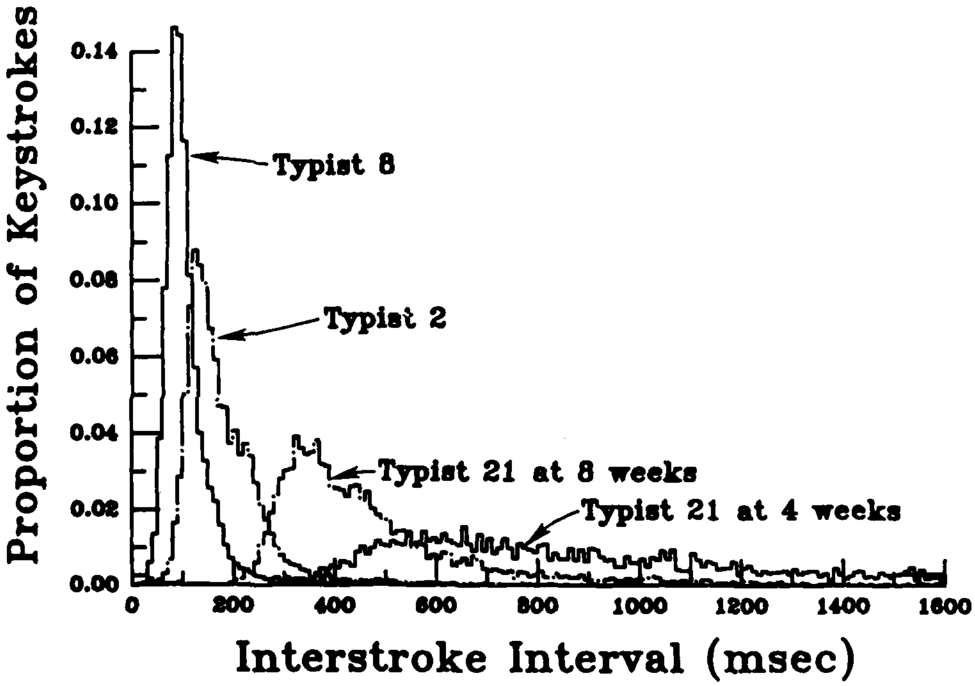


Figure 12. The distribution of all interstroke intervals for Typist 21 after 4 weeks (13 words per minute) and 8 weeks (25 words per minute) of typing class, Typist 2 (66 words per minute) and Typist 8 (112 words per minute).

four classes, a significant qualitative difference became apparent. The relative times to type the four classes were different for beginning and skilled typists. The slowest students typed 1-finger doubles much more rapidly than 1-finger non-doubles, 2-finger or 2-hand digraphs. The fastest typists showed quite a different pattern: 1-finger digraphs, both double and non-double, were typed more slowly than 2-finger and 2-hand digraphs. Figure 13 displays the median interstroke interval of the four digraph classes for all typists studied. Figure 13 also shows a subtler progression for the 2-finger and 2-hand digraphs. In general, 2-hand digraphs were slower than 2-finger, but they tend to be similar for the slowest (below 25 words per minute) and fastest (above 80 words per minute) typists. For the middle range of typists, the median interstroke interval for 2-finger digraphs is about 30% slower than for 2-hand digraphs.

## Learning to Type

The patterns seen when contrasting student, expert, and super typists also hold when the progress of individual students is followed over several weeks. Newell and Rosenbloom (1981) found that, for a wide variety of tasks, a plot of the time to perform the task versus the number of trials produced a straight line in log-log coordinates. The slope of this line (with the sign changed) is the learning rate. Therefore I calculated learning rates by plotting the median interstroke interval against the number of weeks in the typing course. While this is not quite legitimate, because the number of repetitions of a given digraph class varies from week to week, the procedure gives at least a reasonable estimate of the learning rate for these data. Typist 21 was the slowest typist initially and showed the greatest learning rate. Figure 14 shows the improvement of Typist 21 on the different digraph classes over the period of the study. Typist 21's learning rates for 2-finger and 2-hand digraphs were more than twice that for 1-finger digraphs. Six of the eight students had a higher learning rate for 2-finger and 2-hand digraphs than for 1-finger digraphs. Table 1 gives the learning rates of all students for the three digraph classes. On average, compared with 1-finger digraphs, the learning rate was 83% higher for 2-finger digraphs and 54% higher for 2-hand digraphs.

Table 2 shows related data: the median interstroke intervals on Week 4 and Week 8. On Week 4, 1-finger digraphs were fastest, 2-hand digraphs were intermediate, and 2-finger digraphs were slowest. (The only exception to this pattern was Typist 25, who had some previous typing experience and typed at 31 words per minute on Week 4. None of the other students got above 27 words per minute by Week 8, so it is not surprising that Typist 25 exhibited the pattern of a more experienced typist.) Because of the higher learning rate for 2-finger and 2-hand digraphs by Week 8, the median interstroke intervals for the different digraph classes were much closer than on Week 4.

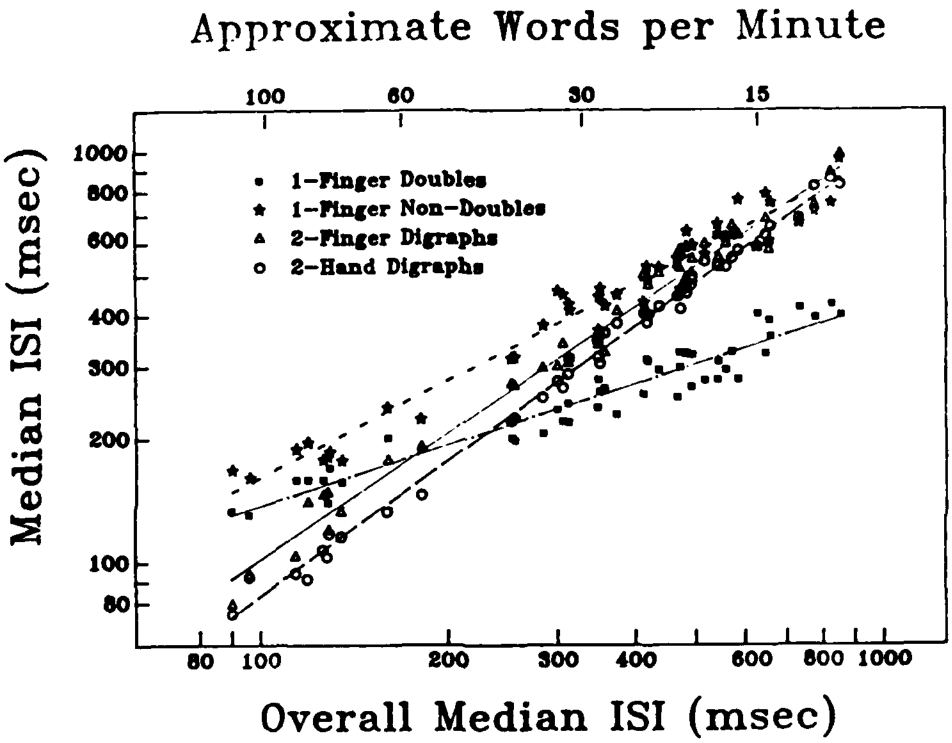


Figure 13. The median interstroke interval for 1-finger doubles, 1-finger non-doubles, 2-finger, and 2-hand digraphs plotted as a function of the typists' overall median interstroke interval. The fastest typist (112 words per minute) is on the left; the slowest typist (13 words per minute) is on the right. The data on the left are from 10 skilled typists; the data at center and right are from 37 sessions with 8 student typists in the fourth through eighth weeks of a beginning typing class. Note that 1-finger doubles are among the slowest for skilled typists but fastest for the students.

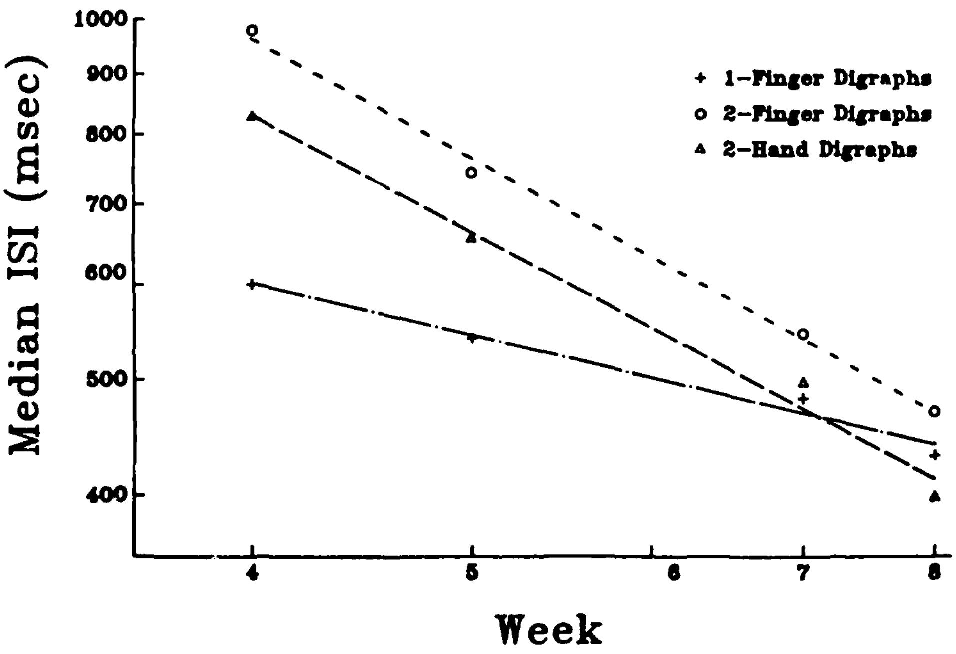


Figure 14. Learning curves for Typist 21 in the fourth through eighth weeks of a beginning typing class. The learning rate for 2-finger and 2-hand digraphs was about twice the learning rate for 1-finger digraphs.

Table 1

Learning Rate

| Typist | Digraph Class 1F | 2F | 2H |
|---|---|---|---|
| 21 | 0.45 | 1.04 | 1.01 |
| 22 | 0.28 | 0.80 | 0.35 |
| 23 | 0.36 | 0.64 | 0.62 |
| 24 | 0.56 | 0.52 | 0.68 |
| 25 | 0.38 | 0.32 | 0.28 |
| 26 | -0.02 | 0.33 | 0.21 |
| 27 | 0.35 | 0.57 | 0.58 |
| 28 | 0.45 | 0.92 | 0.60 |
| Mean | 0.35 | 0.64 | 0.54 |

Note. The learning rate is the slope when the median interstroke interval (msec) is plotted against the time in the typing class (weeks) in log-log coordinates.

Table 2

Median Interstroke Interval (msec)

| | Week 4 | | | Week 8 | | |
|---|---|---|---|---|---|---|
| | Digraph Class | | | Digraph Class | | |
| Typist | 1F | 2F | 2H | 1F | 2F | 2H |
| 21 | 600 | 979 | 828 | 432 | 470 | 398 |
| 22 | 345 | 575 | 412 | 296 | 312 | 313 |
| 23 | 593 | 885 | 857 | 480 | 581 | 586 |
| 25 | 369 | 338 | 265 | 426 | 518 | 448 |
| 26 | 440 | 657 | 549 | 291 | 271 | 220 |
| 27 | 440 | 489 | 463 | 474 | 482 | 450 |
| 28 | 426 | 593 | 523 | 356 | 337 | 315 |
| Mean | 459 | 645 | 557 | 394 | 424 | 390 |

The same developmental pattern is apparent when the individual digraphs are examined, although these data are more variable because of the smaller number of observations. Figure 15 shows some typical examples from Typist 21 for the digraphs ed (1-finger), in (2-finger), and ha (2-hand).

## Variability in Skilled Typing

The keystrokes of skilled typists are remarkably rapid, typically five to eight keystrokes per second. Nonetheless, there is considerable variation in the interstroke intervals. The distribution of interstroke intervals for a typical typist (Typist 4 in this study) had a median of 135 msec and a half-width (the difference between the first and third quartiles) of 58 msec. This section examines the variability of interstroke intervals in transcription typing for skilled typists.

### Effects of the Surrounding Character Context

The interstroke intervals in typing have almost always been categorized in terms of the digraphs being typed. Some authors have subdivided the digraphs, based on the class of finger movements required to type the digraph (Coover, 1923; Kinkead, 1975; Terzuolo and Viviani, 1980; Gentner, 1981a), but the digraph has remained the unit of description. One study that considered wider context beyond the digraph was reported by Shaffer (1978). Shaffer found that the interstroke interval for a given digraph was affected by context both to the left and right of the digraph. I conducted a systematic study of how interstroke intervals are affected by the surrounding character context.

Because interstroke interval distributions are highly skewed, I have followed Shaffer (1973) in characterizing them by medians and quartiles. The spread of an interval distribution was measured in terms of the half-width: the difference between the third and first quartile (the 75th and 25th percentile). I also repeated these analyses using the standard deviation rather than the half-width as a measure of the spread of the distribution, but that did not change any of the results reported here.

Figure 16 shows the distribution of all interstroke intervals for a typical typist. The half-width of the overall distribution is 63 msec. On analysis it became clear, however, that this distribution was a composite of many narrower distributions. When the context of the interstroke interval was highly constrained by fixing the six character string containing the interval (the three characters before and after the interval), the interval distributions had a median half-width of 18 msec. Two such narrower distributions are also shown in Figure 16. Figure 16 illustrates the extremes of context effects, going from no context at all (the distribution of all intervals) to the highly controlled context provided by a string of six characters. Here, I explore the effects of context by determining the half-width of interval distributions as context characters are sequentially added to the left and right of the interval. In a later section, I show that these context

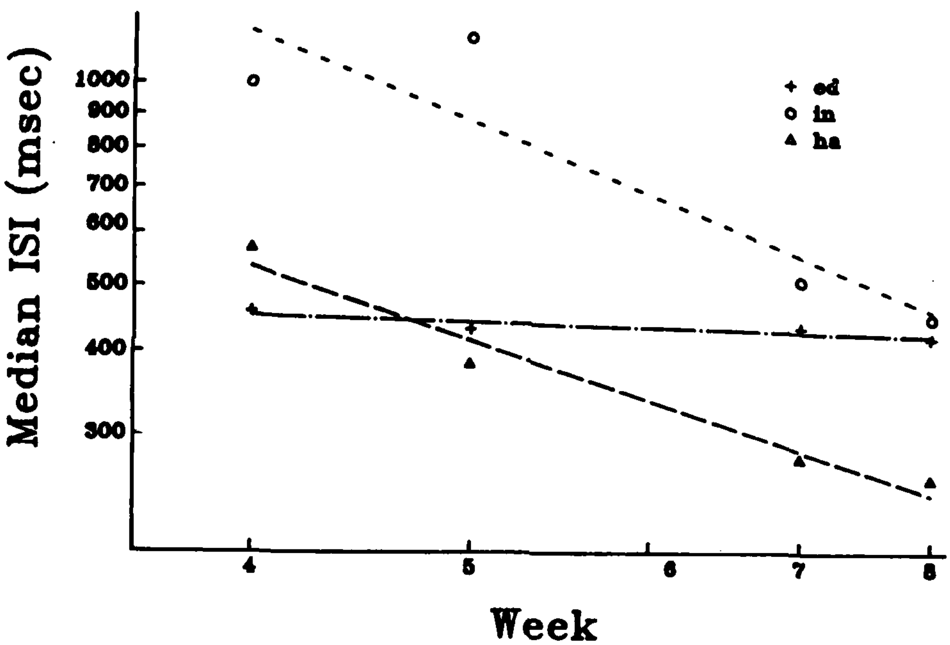


Figure 15. Individual digraph learning curves for Typist 21 in the fourth through eighth weeks of a beginning typing class. The student typist made rapid progress on in (a 2-finger digraph) and ha (a 2-hand digraph), but the median interstroke interval for ed (a 1-finger digraph) changes very little.

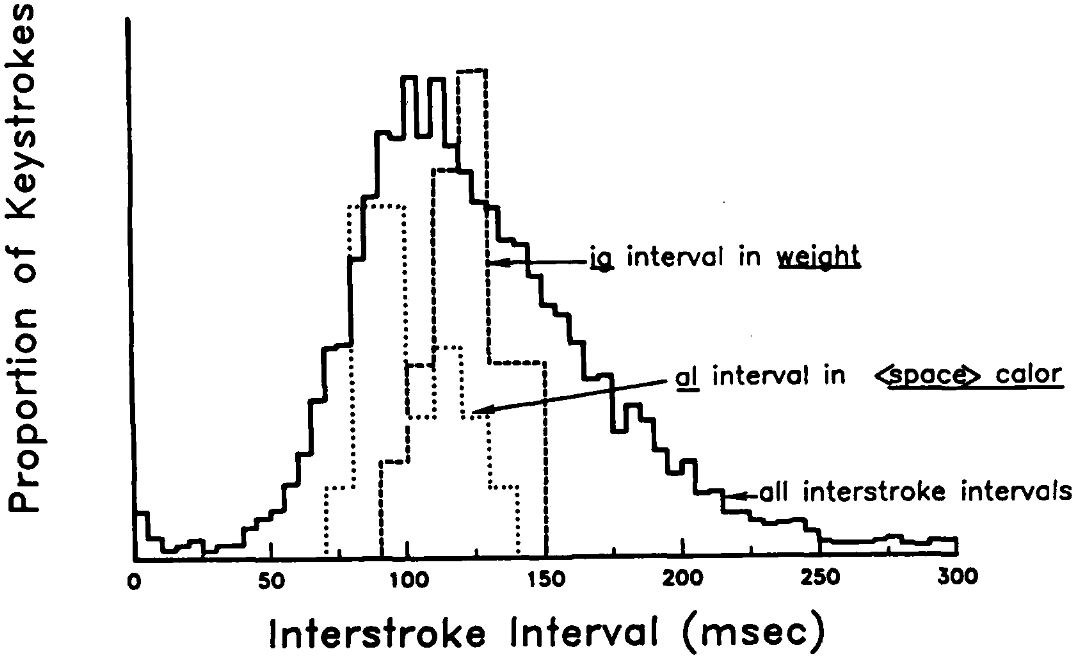


Figure 16. The distribution of all interstroke intervals for Typist 3. This distribution has a half-width of 63 msec. The figure also shows the distribution of intervals for the digraph al in the sequence <space>calor with a half-width of 30 msec, and the distribution of intervals for the digraph ig in the sequence weight with a half-width of 17 msec. The median half-width for all such interval distributions with six characters of context fixed is 18 msec, indicating that the distribution of all interstroke intervals is composed of many narrower distributions with varying medians.

effects are independent of the word unit. It is not the case that controlling the context is effective merely because it helps specify the word in which the digraph occurs.

The effects of specifying context are shown in Table 3. The line labeled "All" gives the half-width of the distribution of all interstroke intervals (the mean half-width across all typists is 56.7 msec). The median half-width of interval distributions for the individual characters, shown on line "C", is the median half-width of the distributions of interstroke intervals ending with a, b, c, etc. The median half-width for individual characters (55.2 msec) is essentially the same as for all characters combined, indicating that specifying the character being typed has little effect on the variability of interstroke intervals. In contrast, specifying one additional character to the left of the character being typed ("cC") reduces the half-width by almost half to 31.7 msec. This is the strongest context effect observed and is the basis for the common practice of describing interstroke intervals in terms of the corresponding digraphs. Table 3 also shows that the effect of context extends further than one character to the left of the character being typed. Specifying a second character to the left ("ccC") further decreases the half-width of the distributions to 25.7 msec. Specifying a third character to the left ("cccC") has little effect. Somewhat surprisingly, context to the right of the character being typed also affects the intervals. It appears from the data in Table 3 that specifying one character ("Cc") or two characters ("Ccc") to the right also reduces the half-width of the interval distributions.

The data in Table 3 are confounded, however. Because the data are based on normal English text, the distribution of letters in words is not balanced and, for example, specifying right context also puts constraints on the left context. To separate these factors, consider the case when the character being typed and two characters to the left are specified ("ccC"). A total of three characters are specified, and the mean half-width is 25.7 msec. A fourth character can be added to the context either by specifying a third character to the left ("cccC") or one character to the right of the typed character ("ccCc"). Adding a character on the left to the context decreases the half-width by 1.4 msec, but adding a character on the right decreases the half-width by 4.7 msec. This effect holds for every individual typist, and indicates that adding context to the right does more than merely constrain left context. A similar argument shows that the second character of right context has little effect (compare line "ccCc" with line "cccCc" versus line "ccCcc"). In summary then, the interstroke interval for typing a given character is influenced by the neighboring two characters to the left and one character to the right.

## Effect of Digraph Class

It is well established that the interstroke intervals differ for the different digraph classes (Coover, 1923; Terzuolo and Viviani, 1980). This analysis is concerned with variability of the interstroke intervals within and among typists.

Table 3

Median Half-Widths of Interval Distributions (msec)

| Fixed String[a] | N[b] | Typist 1 | 2 | 3 | 4 | 5 | 6 | Mean |
|---|---|---|---|---|---|---|---|---|
| All | 1 | 56 | 73 | 63 | 51 | 57 | 40 | 56.7 |
| C | 26 | 57 | 76 | 59 | 50 | 52 | 37 | 55.2 |
| cC | 206 | 35 | 39 | 34 | 30 | 24 | 28 | 31.7 |
| ccC | 238 | 27 | 33 | 27 | 23 | 21 | 23 | 25.7 |
| cccC | 94 | 26 | 29 | 26 | 21 | 22 | 22 | 24.3 |
| Cc | 210 | 44 | 58 | 47 | 41 | 43 | 34 | 44.5 |
| Ccc | 237 | 34 | 40 | 42 | 35 | 38 | 29 | 36.3 |
| ccCc | 94 | 23 | 25 | 23 | 19 | 17 | 19 | 21.0 |
| ccCcc | 58 | 24 | 25 | 19 | 19 | 16 | 18 | 20.2 |
| cccCc | 59 | 23 | 25 | 21 | 19 | 17 | 19 | 20.7 |
| cccCcc | 20 | 25 | 22 | 18 | 20 | 16 | 21 | 20.3 |

Note. Based on all six-character strings composed of lower case letters, period, comma, and space occuring ten or more times in the diet text.

[a] The row labeled "All" is for the distribution of all characters combined. The labels for the other rows specify the fixed string, with "C" indicating the character which terminates the interval and "c" indicating additional context characters. For example, the label "ccC" refers to a series of 238 distributions including the distribution of <u>an</u> intervals in the string <u>tan</u>.

[b] N is the number of distributions analyzed for each typist.

Considering first the question of within-typist variability, 2-finger digraphs as a class were generally more variable than 1-finger or 2-hand digraphs. These data are shown in the first part of Table 4. The mean half-width for 2-finger digraphs is 56 msec, compared with 39 msec for 1-finger and 2-hand digraphs. Examples of these distributions for two typists are shown in Figures 17 and 18.

A different picture emerges, however, if one examines the individual digraph distributions (for example, the distribution of er or do interstroke intervals). The median half-widths of the individual digraph distributions are listed in the middle part of Table 4 . The individual 2-finger and 2-hand digraphs were similar in variability, but they were about twice as variable as the 1-finger digraphs, despite the fact that 1-finger digraphs had a longer interstroke interval. The lower variability of 1-finger digraphs is undoubtedly because the position of the relevant finger is fixed before and after the interval. For example, consider the 1-finger digraph ce and the 2-hand digraph ne. When typing ce, the left middle finger strikes the c key at the start of the interval and the e key at the end, but when typing ne, the position of the left middle finger is undetermined at the start of the interval. The difference in this case is striking: averaged over the typists, the ce distribution has a median of 204 msec and a half-width of 20 msec, but the ne distribution had a median of 120 msec and a half-width of 41 msec.

If 2-finger and 2-hand digraphs were more variable because the finger position was not fixed at the beginning of the interval, controlling the surrounding characters should reduce their variability. The last part of Table 4 shows that this was true. On average, controlling the four-character context surrounding the interstroke interval reduced the half-widths for 1-finger distributions by 15%, but reduced the half-widths for 2-finger and 2-hand distributions by 44% and 36%, respectively. With the context thus controlled, the differences between the three digraph classes were reduced, but 1-finger digraphs were still generally least variable, and 2-hand digraphs were generally most variable.

## Variability among Typists

Table 5 gives the median intervals of 1-finger, 2-finger, and 2-hand digraphs for the six typists. For every typist, 1-finger digraphs were typed slowest, 2-finger digraphs were intermediate, and 2-hand digraphs were typed fastest. The 2-hand digraphs were presumably fastest because typists were able to overlap movements on separate hands. Overlapped movements are obviously not possible for 1-finger digraphs since the same finger is used to type both letters. Overlapping movements for a 2-finger digraph would require independent finger movements on one hand, and I show later that typists vary greatly in the independence of their finger movements.

Table 4

| Median Half-Width of Distribution (msec) | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Typist | | | | | | |
| Digraph Class | 1 | 2 | 3 | 4 | 5 | 6 | Mean |
| | All Interstroke Intervals of a Given Class | | | | | | |
| 1-finger | 32 | 40 | 47 | 34 | 47 | 33 | 38.8 |
| 2-finger | 67 | 79 | 57 | 57 | 41 | 37 | 56.3 |
| 2-hand | 41 | 47 | 39 | 36 | 36 | 34 | 38.7 |
| | Individual Digraph Specified | | | | | | |
| 1-finger | 21 | 21 | 20 | 16 | 20 | 19 | 19.5 |
| 2-finger | 37 | 47 | 36 | 31 | 24 | 30 | 34.2 |
| 2-hand | 38 | 41 | 36 | 35 | 33 | 30 | 35.5 |
| | Digraph Plus Two Surrounding Characters Specified | | | | | | |
| 1-finger | 15 | 21 | 12 | 17 | 15 | 19 | 16.5 |
| 2-finger | 21 | 28 | 17 | 17 | 15 | 18 | 19.3 |
| 2-hand | 28 | 25 | 27 | 19 | 19 | 19 | 22.8 |

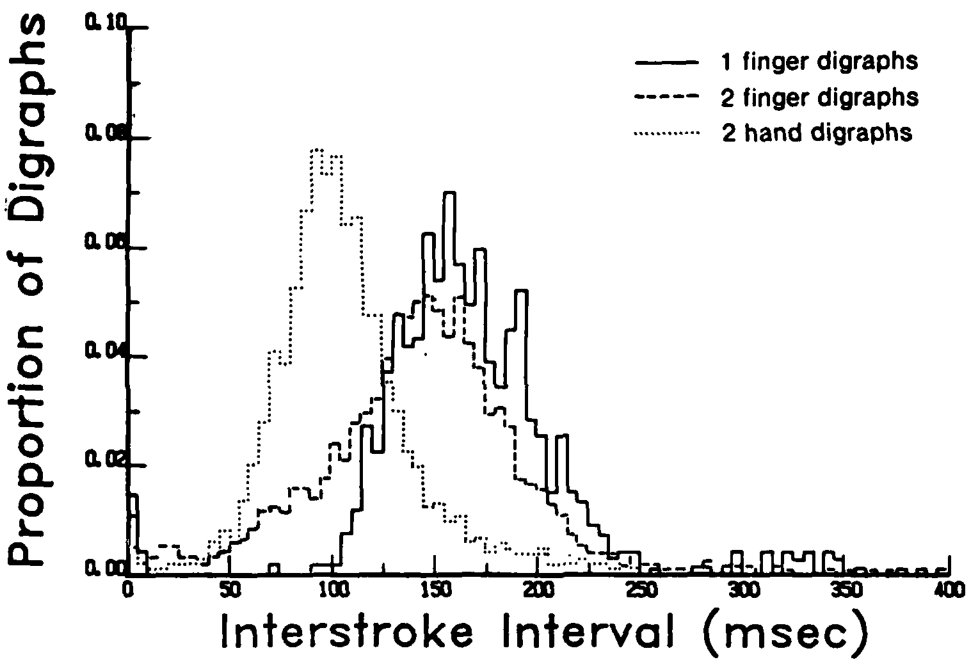


Figure 17. The distribution of interstroke intervals for all lower case letter-letter digraphs for Typist 3. The interstroke intervals for 1-finger digraphs (median = 164 msec) were generally longer than for 2-hand digraphs (median = 103). The distribution for 2-finger digraphs (median = 147) was most similar to that for 1-finger digraphs. The interstroke intervals of less than 5 msec were all errors, when an adjacent key was struck at approximately the same time as the correct key.

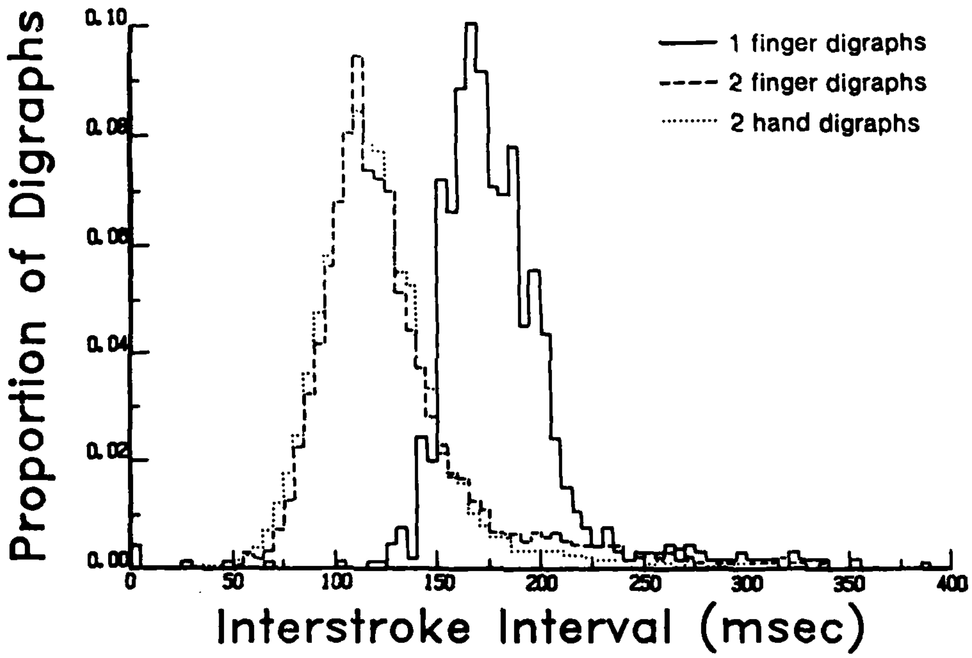


Figure 18. The distribution of interstroke intervals for all lower case letter-letter digraphs for Typist 6. The interstroke intervals for 1-finger digraphs (median = 176 msec) were generally longer than for 2-hand digraphs (median = 117). In contrast to Typist 3, however, the interval distribution for 2-finger digraphs (median = 119) was almost identical to that for 2-hand digraphs. The distributions for the other four typists were intermediate between these extremes.

Table 5

Letter-Letter Digraphs

| Typist | Median Interstroke Interval (msec) Overall | 1-finger | 2-finger | 2-hand | Savings[a] |
|---|---|---|---|---|---|
| 1 | 114 | 180 | 103 | 94 | 90% |
| 2 | 160 | 225 | 176 | 132 | 52% |
| 3 | 128 | 164 | 147 | 103 | 28% |
| 4 | 135 | 167 | 132 | 115 | 67% |
| 5 | 181 | 209 | 190 | 145 | 30% |
| 6 | 129 | 176 | 119 | 117 | 97% |
| 7 | 81 | 157 | 79 | 75 | 95% |
| 8 | 96 | 149 | 93 | 92 | 98% |
| 9 | 117 | 183 | 139 | 91 | 48% |
| 10 | 129 | 168 | 145 | 107 | 38% |
| Mean | 127 | 178 | 132 | 107 | 64% |
| s.d. | 28.7 | 23.3 | 35.1 | 20.9 | |

[a] $\text{savings} = \dfrac{\text{1-finger interval} - \text{2-finger interval}}{\text{1-finger interval} - \text{2-hand interval}}$

As shown by the standard deviations in Table 5, intervals for 2-finger digraphs were most variable among typists. This pattern is even more pronounced when the surrounding character context is controlled. I calculated the standard deviation across the six expert typists for all digraphs appearing ten times or more in the same four-character context. For example, I calculated the standard deviation across typists of the median interstroke intervals for ve in the string ever. The median standard deviations were 24.0 msec for 1-finger digraphs, 39.8 msec for 2-finger digraphs, and 22.8 msec for 2-hand digraphs. That is, 2-finger digraphs are about twice as variable across typists as 1-finger or 2-hand digraphs.

Table 5 also shows that the six typists vary when the interval for 2-finger digraphs is compared to the intervals for 1-finger and 2-hand digraphs. If the difference between 1-finger and 2-hand intervals is taken to represent 100% of the savings resulting from the possibility of overlapping movements, the percent of savings seen in the 2-finger intervals ranges from 28% for Typist 3 to 98% for Typist 8. Note that Typist 3 and Typist 6, who are near the extremes in the amount of savings for 2-finger digraphs (28% and 97%), had similar overall typing rates (76 words/min for Typist 3 and 82 words/min for Typist 6).

The differences in median interstroke interval for the digraph classes are reflected in the distributions of interstroke intervals, shown in Figures 17 and 18 . For Typist 3, the 2-finger digraphs were most similar to the 1-finger digraphs. Typist 6 shows a completely different pattern; the 2-finger digraphs were almost identical to 2-hand digraphs. Figure 19 presents a more detailed comparison of the 77 highest frequency digraphs in the diet text for Typists 3 and 6. Typist 3 was faster on 1-finger and 2-hand digraphs and Typist 6 was faster on 2-finger digraphs.

Variabililty in Finger and Hand Movement

All six expert typists were faster when typing 2-hand digraphs than when typing 1-finger digraphs. Because there is no possibility of overlapping the successive keystrokes in 1-finger digraphs and because typists have been observed to overlap keystrokes with 2-hand digraphs (Olsen & Murray, 1976; Gentner, Grudin, & Conway, 1980), the shorter interval of 2-hand digraphs has been attributed to overlapped movements. This perspective suggests that the variation in the relative interval of 2-finger digraphs could be caused by a variation in different typists' ability to overlap movements within a hand.

To examine this issue, I determined the typists' finger and hand movements from the videotape recordings. I analyzed the finger and hand trajectories during typing a letter sequence that appeared a number of times in the diet text. The string thing occurred eight times in various words in the diet text. The actual words were: things (twice), anything (twice), nothing (twice), thing, and everything. Figure 20 shows the trajectories of the right index finger while typing hin in the string thing. (The right index finger types h and n; the right middle

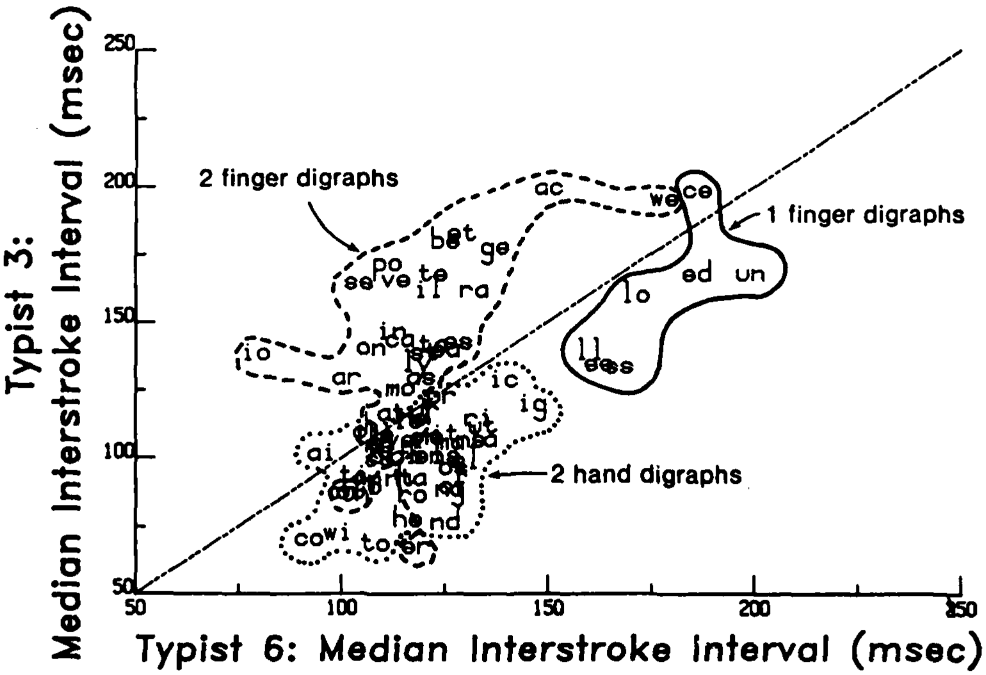


Figure 19. Comparison of the median intervals of the 77 highest frequency digraphs for typists 3 and 6. Digraphs plotted below the diagonal line were typed faster by Typist 3, while those above the diagonal were typed faster by Typist 6. Although Typist 3 was faster with 1-finger and 2-hand digraphs, Typist 6 was faster with 2-finger digraphs. Their overall typing rates were similar.

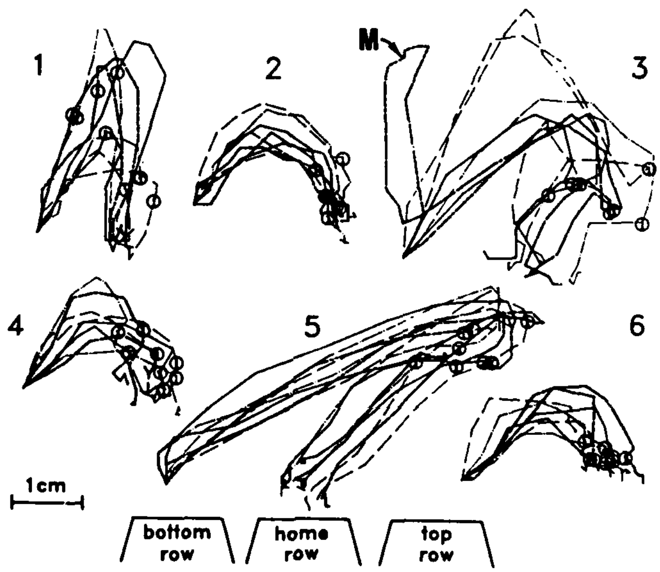


Figure 20. Trajectories of the right index finger while typing the sequence hin in the string thing for Typists 1 through 6. The projection of trajectory on the Y,Z plane is shown, as if the finger was viewed from the right end of the keyboard (see KEYBOARD FIGURE). The letters h (the right end of the trajectory) and n (the left end of the trajectory) are typed by the right index finger. The circled "i" indicates the time when the i key was struck by the right middle finger. The trajectories have been adjusted to superimpose their end points, when the n was struck. The approximate location of the typewriter keys, relative to the finger trajectory for Typist 5, is indicated at the bottom of the figure. Eight finger trajectories are shown for each typist except Typist 3, who made an error in one of the words. Another trajectory of Typist 3 (labeled "M" in the figure) contains an apparent misstroke and was not included in the analysis.

finger types the i. See KEYBOARD FIGURE for the keyboard layout.) The finger trajectories of Typists 2, 4, and 6 appear similar: direct, regular, smooth movements of the index finger from the h key to the n key. This can be seen quantitatively in Table 6. The means and standard deviations of the path length were smallest for Typists 2, 4, and 6. By contrast, Typists 1 and 3 had longer and more variable finger trajectories. Typist 5 had the longest finger trajectories of all (almost three times those of Typist 6), although they were fairly regular relative to their length.

There was a general correlation between the length of the finger trajectory and the time between striking h and n. Comparing typists, the correlation between the mean path length and the mean hn interval was +0.75 (non-significant), and the correlation increased to +0.95 when Typist 2 was excluded. When the keystrokes were compared separately for each typist, path length and interval were significantly correlated for Typists 1, 3, and 4 (mean $r$ = +0.85), but the correlations were insignificant, although still reasonably high, for Typists 2, 5, and 6 (mean $r$ = +0.55).

A final observation of note is that, for a given typist, the time between striking the h and n is more regular than the length of the finger trajectory. Taking the ratio of the standard deviation to the mean as a measure of relative variability, the mean variability in path length (0.141) for the six typists was about twice the mean variability in hn interval (0.087). The path length was more variable than the interstroke interval for all typists except for Typist 2.

An earlier section of this paper contrasted 2-finger and 2-hand digraphs in terms of interstroke intervals. This section extends the contrast to observations of finger and hand movements. Consider the sequences hin and hen. The within-hand sequence, hin, is composed of 2-finger digraphs, and the alternating-hand sequence, hen, is composed of 2-hand digraphs. Although typists are generally faster at typing alternating-hand sequences than within-hand sequences, I showed earlier that there are large individual differences in the extent to which 2-hand digraphs are faster than 2-finger digraphs. I found similar differences when comparing the sequences hin and hen. The times to type hin and hen are compared in Table 7.

Typists 2, 4, and 6, who displayed the short, regular finger trajectories, actually typed the sequence hin an average of 12% faster than the sequence hen. This shows that within-hand sequences are not necessarily slower than alternating-hand sequences. One reason for these fast performances may be that hin is a high frequency trigram, in the top 4% of trigrams listed by Underwood and Schulz (1960). High frequency digraphs such as er and hi were usually among the most rapidly typed digraphs despite the fact that they are typed by one hand.

Table 6

Variability in Typing "hin"

| Typist | Finger Path Length (mm) | | | Interstroke Interval (msec) | | |
|---|---|---|---|---|---|---|
| | Mean | SD | SD/Mean | Mean | SD | SD/Mean |
| 1 | 56.4 | 12.9 | .229 | 231 | 10.7 | .046 |
| 2 | 41.3 | 3.7 | .090 | 298 | 31.9 | .107 |
| 3 | 90.8 | 19.5 | .215 | 279 | 47.9 | .172 |
| 4 | 41.5 | 4.4 | .106 | 201 | 10.2 | .051 |
| 5 | 108.8 | 8.7 | .080 | 349 | 17.9 | .051 |
| 6 | 38.5 | 4.9 | .127 | 213 | 20.0 | .094 |
| Ave. | | | .141 | | | .087 |

Table 7

| Median Interstroke Intervals (msec) | | | | | | |
|---|---|---|---|---|---|---|
| | Typist | | | | | |
| Interval | 1 | 2 | 3 | 4 | 5 | 6 |
| hin in thing | 231 | 289 | 261 | 197 | 346 | 223 |
| hen | 191 | 329 | 196 | 255 | 294 | 241 |
| hin/hen | 1.25 | .89 | 1.38 | .81 | 1.19 | .93 |
| All hi | 82 | 125 | 113 | 105 | 155 | 109 |
| All in | 78 | 144 | 148 | 102 | 190 | 112 |
| hi in thing | 160 | 131 | 114 | 100 | 145 | 107 |
| in in thing | 76 | 160 | 146 | 102 | 202 | 108 |

In contrast with the performance of Typists 2, 4, and 6, Typists 1, 3, and 5 were about 27% slower when typing hin compared with hen. In all three cases, interference between movements to type the i and n appeared to be responsible for the slower performance when typing hin. Figure 20 shows that Typists 3 and 5 moved their right index finger toward the top row of the keyboard while typing the i with their right middle finger. After striking the h key, Typists 3 and 5 typically moved their index fingers 10 and 30 mm, respectively, in the direction of the top row. This forces a much longer movement to type the n. In contrast, the average movement toward the top row by Typists 2, 4, and 6 was less than 1 mm. Thus, it appears that Typists 3 and 5 are slower because the movement of the right middle finger interfers with, and delays, the movement of the right index finger.

The case of Typist 1 was more puzzling at first. Typist 1 usually typed 2-finger digraphs almost as fast as 2-hand digraphs (see Table 5), yet she typed hin 25% slower than hen. The clue came from the analyses in Table 7. Note that the interstroke intervals observed for hin were essentially identical to the normal hi and in interstroke intervals in every case except one: for Typist 1 the median hi interval was 82 msec, but it was 160 msec in the sequence hin. When I checked all of the timing data for Typist 1, I found that the mean hi interval was 165 msec when hi was followed by n or m, but 72 msec when followed by any other letter. The two distributions do not overlap at all. No other typist showed this large difference, although the difference of the means for Typist 2 (137 msec versus 117 msec) was statistically significant. An analysis of the hand movements of Typist 1 suggests that typing the n interfered with typing the i. After striking the h key, the other typists usually kept the hand fixed or moved it toward the upper row while striking the i key. On average, Typists 2 through 6 moved the hand 3 mm toward the upper row before striking the i. Typist 1, however, actually moved the hand toward the lower row of the keyboard an average of 6 mm before striking the i key. Presumably this made the i a longer and more difficult keystroke. For each typist, movement of the hand toward the top was correlated (non-significantly) with a short hi interstroke interval. This correlation was greatest (0.61) for Typist 1. The difference in hand motion is reflected in the finger trajectories shown in Figure 20. The index fingers of Typists 2 through 6 were above the middle or upper row of the keyboard when the i is struck, but the index finger of Typist 1 was half way to the n key before the i is struck. Another related observation is that for Typist 1, and none of the other typists, the time between the h and n keystrokes was more regular (standard deviation = 10.7 msec) than either the hi interval (SD = 35.5 msec) or the in interval (SD = 27.4 msec). It is as if the sequence hn had been programmed, with the i keystroke allowed to fall somewhere in between.

The quantitative measures of finger movement reported above describe the movement of the fingertip relative to the keyboard. This movement can be decomposed into a movement of the hand relative to the keyboard and a movement of the fingertip relative to the hand.

Table 8 lists the amount of hand movement and the amount of finger movement relative to the hand for each typist during the sequence hin. The table also lists the ratio of relative finger to hand movement, calculated for each movement individually, and the ratio of hin/hen time intervals. The range extends from Typist 3, who had about equal amounts of finger and hand movements, to Typist 4 whose finger movements were more than twice the size of her hand movements. Comparing across typists, the amount of hand movement was significantly correlated ($r$ = +0.89) with the hin/hen interval. Typists with less hand movement typed hin relatively faster.

## Models of Keystroke Timing

### No Evidence for a Word Level

Terzuolo and Viviani (1980) showed that, in a number of cases, the interstroke interval for a given digraph differed significantly depending on the word in which it was embedded. For example, they report that for one typist, the an interstroke interval (the time between the a and n keystrokes) was 147 msec in the word thank, but 94 msec in the word ran. They cite these differences as evidence for a word-specific, stored timing pattern. An alternative explanation, however, is that the interstroke interval could be modulated at the time of execution by the surrounding character context, without requiring any stored timing pattern. In the word thank, for instance, it could be that the right index finger types the n more slowly than usual because it was recently occupied with typing the h. (KEYBOARD FIGURE shows the standard typewriter keyboard layout.) There would be no comparable delay in the word ran because the r and a are typed by the left hand, giving the right index finger plenty of time to position itself over the n key.

An earlier section described in detail the effects of surrounding character context on the interstroke interval. It could be argued that the interstroke interval for a given digraph is specific to the word, and in specifying the context we are merely limiting the set of words in which the digraph occurs. There are three major lines of evidence against this argument: first, the effects of context cross word boundaries; second, intervals in the same context, but in different words, do not differ; third, context effects can be produced without word-specific timing patterns.

First, the effects of context cross word boundaries. To determine whether context effects apply only within words or could also be found between two words, I compared cases in which the left context was within the word with cases where it crossed a word boundary. As indicated in Table 9, the half-widths of distributions for intervals preceding lower case letters narrowed as the left context was further specified (compare line "C" with line "cC" and line "_C"). The character context was clearly more effective than the space context: reducing the half-width to a mean of 30.8 msec, compared to 42.7 msec for the space context. The important point for this analysis, however, is that specifying a

Table 8

| Median Path Lengths (mm) | | | | | | |
|---|---|---|---|---|---|---|
| | Typist | | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 |
| Right Hand | 32.9 | 25.4 | 54.2 | 17.1 | 49.5 | 20.5 |
| Right Index Finger (relative to Hand) | 44.6 | 35.2 | 65.5 | 38.4 | 98.4 | 37.6 |
| Median Finger/Hand Ratio | 1.21 | 1.38 | 1.14 | 2.28 | 1.92 | 1.86 |
| hin/hen Interval Ratio | 1.25 | 0.89 | 1.38 | 0.81 | 1.19 | 0.93 |

Table 9

Context Effects Within and Across Words
Median Half-Widths of Interval Distributions (msec)

| Fixed String[a] | N[b] | Typist 1 | 2 | 3 | 4 | 5 | 6 | Mean |
|---|---|---|---|---|---|---|---|---|
| C | 23 | 57 | 74 | 56 | 50 | 51 | 37 | 55.2 |
| cC | 161 | 35 | 37 | 32 | 28 | 24 | 29 | 30.8 |
| ccC | 104 | 27 | 30 | 25 | 21 | 21 | 22 | 24.3 |
| _C | 20 | 45 | 50 | 53 | 50 | 32 | 26 | 42.7 |
| c_C | 36 | 33 | 41 | 50 | 37 | 28 | 23 | 35.3 |

Note. Based on all strings composed of six lower case letters occurring 10 or more times in the diet text. Some of the half-widths in this table are slightly different from the corresponding half-widths in Table 1 because "C" and "c" in Table 1 include lower case letters, period, comma, and space, but "C" and "c" in this table are restricted to lower case letters only.

[a] The labels specify the fixed string with "C" indicating the letter terminating the interval and "c" indicating additional context characters. For example, the label "c_C" refers to a series of 36 distributions including the distribution of <space>t intervals in the string e<space>t.

[b] N is the number of distributions analyzed for each typist.

second character of left context further reduced the half-width of the distributions by similar amounts whether the intervening character was a lower case letter or a *space*. When it was within-word context ("ccC"), the second character of context reduced the half-width by 6.5 msec on average, and when it was cross-word context ("c_C"), the second character of context reduced the half-width by 7.4 msec. Context effects crossed word boundaries for all six typists.

In accord with this result, Shaffer (1978) found that the initial interval in a word could be affected by the previous word. For example, the mean <space>*s* interval was 91 msec in the phrase *win supply* but 121 msec in the phrase *ratio supply*. He found significant effects of the previous word in 12 of the 39 cases examined. Shaffer's results indicate not only that context effects can cross word boundaries, but that the pattern of intervals found in a given word is dependent on the previous word--additional evidence against a word-specific timing pattern.

*Second, intervals in the same context, but in different words, do not differ*. I examined all words in the diet text that shared a string of four or more letters to see if there would be any effect of the word being typed, once two letters of left context and one letter of right context were specified. For example, I compared the *er* interval in the words *permanent* and *supermarket*. Since the text was not specifically chosen for this test, the number of possible comparisons was small. Nonetheless, out of 77 pairs of intervals compared in the same context but in different words, none of the means were significantly different at the 5% level. Although a null result is never very convincing, this finding supports the view that it is the surrounding character context, rather than the word, that determines the interstroke interval.

*Third, context effects can be produced without word-specific timing patterns*. Examination of the typewriter keyboard (KEYBOARD FIGURE) suggests how these wider context effects can be accounted for without having to postulate word-specific timing patterns. Consider the *it* interval in the sequences *bit* and *wit*. The typing of the *t* by the index finger on the top row could be delayed in the sequence *bit*, relative to the sequence *wit*, because the index finger is pulled away from the top row to type the *b* on the bottom row (the *w* is typed by the left ring finger on the top row). Five of the six typists had a longer median *it* interval in the sequence *bit* (mean over typists = 130 msec) than in the sequence *wit* (mean = 112 msec). The means were significantly different by a *t* test ($P < 0.05$).

It is less obvious how context to the right of the digraph could affect intervals. To see how this might come about, consider the sequences *tin* and *tio*. The *i* and *o* are typed by the right hand on the top row, but the *n* is typed by the right hand on the bottom row. If the attempts to type neighboring letters overlap somewhat in time, we could expect the *ti* interval to be longer in the sequence *tin*; a tendency to move to the bottom row to type the *n* would conflict with the movement to the top row to type the *i*. This conflict would not exist when typing the sequence *tio*. All six typists had a longer median *ti* interval in

the sequence tin (mean over typists = 126 msec) than in the sequence tio (mean = 100 msec). The means were significantly different by a *t* test ($P < 0.01$).

These data from typists are supported by results from the simulation model of typing developed by Rumelhart and Norman (this volume). Their simulation model has no word-specific timing patterns. Instead, keystroke timing is determined by the layout of the keyboard and the physical constraints of the hands and fingers, which may be attempting to type several letters at once. Rumelhart and Norman report effects of right context very similar to those obtained by Shaffer. I did several experiments with their computer simulation model, having it type the diet text as well as specially controlled texts. I found context effects from characters two to the left and one to the right similar to those shown by typists. For instance, the mean it interval produced by the simulation model in the sequence bit was 1.6 times as long as in the sequence wit. The mean ti interval in the sequence tin was 1.3 times as long as in the sequence tio. In both cases the means were significantly different by a *t* test.

## Parallel versus Serial Models of Keystroke Timing

The presence or absence of a unit larger than the individual keystroke has been a recurrent issue in studies of keystroke timing. That is, is the time for a given keystroke specified in parallel with a larger sequence of keystrokes, or is it specified serially, relative only to the previous keystroke? At the extreme of parallel models, the unit could be the entire sequence to be typed, and all times would be specified relative to the beginning of typing. Wing and Kristofferson (1973; Wing, 1980) developed a metronomic model of finger tapping on this basis, with the times of each response in the sequence related to an internal timekeeper. Shaffer (1978) argued for a metronomic model of timing based on data from one fast typist. In a series of papers, Terzuolo and Viviani (1979; 1980; Viviani & Terzuolo, 1980) proposed a parallel model of typing with the word as the basic unit.

In the simple parallel model, the times of successive keystrokes are independent. The time for the *n*th keystroke is given by

$$t_n = T_n + e_n \tag{1}$$

The interstroke interval for the *n*th keystroke is

$$i_n = t_n - t_{n-1} = T_n - T_{n-1} + e_n - e_{n-1} \tag{2}$$

where

$t_n$ is the observed time of the *n*th keystroke.

$T_n$ is the planned time of the nth keystroke.
$e_n$ is a random error term for the nth keystroke.
$i_n$ is the observed interstroke interval for the nth letter of the unit.

Note that, in Equation 2, the error term $e_{n-1}$ enters into $i_n$ with a negative sign, but would enter into $i_{n-1}$ with a positive sign. This relation leads to a negative correlation between successive interstroke intervals for parallel models of timing. (For further discussion of the negative correlations in parallel timing models, see Wing, 1980 and Gentner, 1981b.)

In the corresponding serial model,

$$t_n = t_{n-1} + I_n + e_n \tag{3}$$

and

$$i_n = I_n + e_n \tag{4}$$

where $I_n$ is the planned interstroke interval of the nth keystroke.

In this simple serial model, successive interstroke intervals are independent and uncorrelated.

It would be easy to distinguish between these simple parallel and serial models on the basis of the correlation between successive keystrokes. Other factors however, complicate the analysis. For example, fluctuations in the overall typing rate over time will make the correlations more positive for both models.

I calculated the correlation between successive interstroke intervals for all expert and super typists while transcribing the diet text. These data are shown in Table 10. The correlations were all positive, ranging from 0.05 to 0.34, with a mean of 0.16. The large variations in interstroke interval caused by differences in the digraph and surrounding context contribute a lot of noise to these correlations, however, so I also calculated the correlations for successive intervals in repeated typings of several common letter strings. I examined both within-hand sequences (ever, ion<space>, <space>you) and alternating-hand sequences (<space>and<space>, <space>for<space>, ight<space>, <space>the<space>, <space>with. These data are from an earlier, similar study in which Typists 1 thru 5 transcribed six magazine articles. The results are shown in Table 11. Overall, the correlations were mostly positive, with within-hand sequences exhibiting more positive correlations than alternating-hand sequences, but this pattern does not hold for every typist.

Table 10

Correlation between
Successive Interstroke Intervals
for Entire Text

| Typist | Correlation |
|---|---|
| 1 | 0.171 |
| 2 | 0.318 |
| 3 | 0.134 |
| 4 | 0.154 |
| 5 | 0.088 |
| 6 | 0.341 |
| 7 | 0.124 |
| 8 | 0.052 |
| 9 | 0.217 |
| 10 | 0.036 |
| Mean | 0.164 |

Note. Interstroke intervals greater than 800 msec (1.2%) were excluded.

Table 11

Correlations between
Successive Interstroke Intervals
for Repeated Letter Strings

| Typist | Within-Hand Sequence | Alternating-Hand Sequence |
|---|---|---|
| 1 | -0.16 | -0.01 |
| 2 | 0.38 | 0.45 |
| 3 | 0.23 | -0.19 |
| 4 | 0.12 | 0.14 |
| 5 | 0.40 | 0.03 |
| Mean | 0.19 | 0.08 |

The more negative correlations observed with alternating-hand sequences need not be an indication of parallel timing control. For example, if timing across hands is more variable than timing within a hand, then in alternating sequences, such as the, the th and he intervals will be negatively correlated. This is the case for some of the typists. For Typists 1 and 3, the te intervals in the word the were actually less variable than the th or he intervals, leading to large negative correlations of -0.5 to -0.7 for the th versus he intervals. For these two typists, the time between striking t and e in the was almost identical to a normal te interval, for instance in the word tell. In contrast, for the other eight expert and super typists, the te interval in the was much longer than a normal te interval. This again suggests that when Typists 1 and 3 type the word the, the left hand types the sequence te with timing relatively independent of the typing of the h by the right hand.

## Discussion

The layout of the typewriter keyboard and the physical constraints of the hands appear to be the most important determinants of keystroke timing in skilled typing. When two successive keys are typed by the same finger (1-finger digraphs), there is no possibility of overlapping the two movements in time, and these digraphs have the slowest interstroke intervals. If the two successive keys are typed by different fingers on the same hand (2-finger digraphs) or different hands (2-hand digraphs), the second movement can overlap the first movement in time or at least be unaffected by the first movement. Skilled typists typically type 2-finger and 2-hand digraphs with interstroke intervals 3/4 to 1/2 the length of those required for 1-finger digraphs.

The pattern is just the opposite for beginning typists. The interstroke intervals for 2-finger and 2-hand digraphs are much slower than for 1-finger digraphs. A likely possibility is that the limiting factor for student typists is the time to plan and coordinate movements, and that these processes take longer when two fingers are involved. As student typists get more practice, they move toward the physical limits that dominate the performance of skilled typists.

Although skilled typists share many characteristics, they also exhibit surprisingly large differences, both within and across typists, that have not been eliminated by thousands of hours of practice. Considered as classes, the interstroke intervals of 2-finger digraphs were the most variable for a given typist. When the digraph and the surrounding context were controlled, however, all digraphs classes were much less variable. Averaged over typists, the median half-widths of the interstroke interval distributions were 16.5, 19.3, and 22.8 msec for 1-finger, 2-finger, and 2-hand digraphs, respectively. These differences suggest that timing is most accurately programmed when the action involves one finger, intermediate when it involves two fingers on one hand, and least accurate when it involves two hands. An alternate explanation is that 2-hand digraphs are more variable because factors such as the relative elbow position are not being controlled, but they

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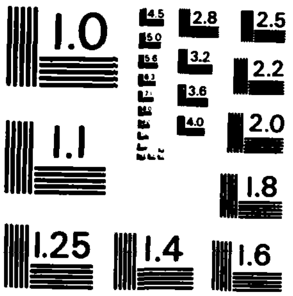


MICROCOPY RESOLUTION TEST CHART
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are of necessity controlled for 2-finger and 1-finger digraphs that only involve one hand. According to this second explanation, it is the execution of the action, rather than the programming of it, that is responsible for the observed differences in variability.

The interstroke intervals for 2-finger digraphs were the most variable between typists. For some typists they were like the rapid 2-hand digraphs; for other typists they were like the slow 1-finger digraphs; for the remaining typists, 2-finger digraphs were intermediate in speed. These differences were not always related to overall typing speed. Typists 3 and 6 were near the extremes for the speed of 2-finger digraphs relative to 2-hand digraphs, but had similar overall typing rates. Analysis of finger and hand movements on videotape recordings showed that the differences in relative speed for 2-finger digraphs were correlated with the independence of within-hand finger movements. Three typists who moved their fingers independently were able to type a within-hand sequence (hin) as rapidly as an alternating-hand sequence (hen). The other three typists coupled their within-hand finger movements. When typing a 2-finger digraph, the movement to strike the first key often interfered with the movement of another finger to strike the second key. In general, the typists who show independent within-hand finger movements have higher overall typing speeds, but there are clearly exceptions to this rule.

In the cases studied, the time period of a movement was generally more regular than the path length of the movement. This suggests that it is the time parameters of the movement, rather than the spatial parameters, that are specified by the motor program. Kelso, Southard, and Goodman (1979) came to a similar conclusion with a very different task. They had subjects move two hands toward different targets and found that, although the speed and distance of the movements varied widely, the time patterns of the two movements were in synchrony.

There is no evidence from keystroke timing for the importance of word level or higher level units. The sequence of letters being typed, as it establishes the interaction between keyboard layout and the physical constraints of the hand, is the primary determinant of keystroke timing for skilled typists. Serial models of timing provide a better fit to the data than parallel models, but that appears to be primarily a reflection of the semi-serial nature of the finger movements. Thus, within-hand sequences, where the physical constraints are more likely to enforce sequential movements, generally fit a serial model of timing better than alternating-hand sequences.

Transcription typing was originally appealing because of its simple, highly repetitive nature. On closer examination, it is a complex process with performance strongly dependent on task context, and with large individual differences between skilled typists. Perhaps we were a little misled by viewing typing at the level of the keystroke, with its discrete outcome (the typed letter) and an exact, if somewhat arbitrary time. The keystroke is a narrow window into a skill involving reading, mental processing, planning, coordination, and execution of continuous movements.

# ERROR PATTERNS IN SKILLED AND NOVICE TRANSCRIPTION TYPING[10]

Jonathan T. Grudin

Errors have long been viewed as an important source of evidence for the organization underlying performance. In this study, the general patterns of errors made by novice and expert typists suggest how skill in this complex motor task is organized and developed.

Early accounts of typing errors were largely descriptive (e.g., Lessenberry, 1928; Dvorak et al., 1936). Lashley's (1951) suggestion that they are a potentially valuable source for inferring the processes in skilled performance was picked up in the 1960s and thereafter: MacNeilage (1964), Shaffer and Hardwick (1968, 1969), Long (1976), and Rabbitt (1978). Sophisticated process models for typing have been proposed (e.g., Shaffer (1978); Sternberg, Monsell, Knoll, & Wright, 1978; Terzuolo & Viviani, 1980; Rumelhart & Norman, 1982). The increased availability of computer and video systems, which are particularly suited for analysis of typewriting, makes it possible to correct and extend previous accounts. This study goes beyond initial descriptive categorizations to suggest functional classifications that support the divisions of the Glossary in this volume and to support constraints on a model of typing explored elsewhere (Grudin, 1981).

Lessenberry (1928) compiled letter confusion matrices in which 60,000 typing errors are categorized according to the letter intended and the letter actually struck. I have extended the analyses of Lessenberry's data and compiled two additional confusion matrices to allow a more detailed comparison of novice and expert performance.

One of my tables was constructed from all substitution errors found in a large corpus of text transcribed by expert typists. The second consisted of all substitution errors from a practice exercise by about seventy beginning high school typists. These confusion matrices are in the Appendix.

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I thank Craig Will and Don Gentner for their assistance and many discussions, Don Norman for his advice and contributions, and the LNR Research Group for its encouragement and support of this work. I also thank the typists who contributed to these studies, including students in typing classes conducted by James Henderson at La Jolla High School. Mark Wallen developed software, Patty Haden assisted with data analysis, and Eileen Conway with manuscript preparation.

## The Lessenberry Confusion Matrix

Important contextual information is lost when only the key intended and the key actually struck are considered. As Dvorak, Merrick, Dealey, and Ford (1936) mentioned, the context usually supplies information necessary for determining the cause of a given error. Nevertheless, some patterns emerge from Lessenberry's large corpus.

The correct character was replaced by a character immediately adjacent and in the same row in 43% of the errors. (These are referred to as row errors.) Substitution of a neighboring letter from the same column (column errors) accounted for 15%.

Most common after neighboring letters is the substitution of the homologous ("mirror-image") letter, typed by the same finger in the same position but the wrong hand. This error is typically the second or third most frequent substitution. It accounts for 10% of the errors overall, even though several letters have no corresponding homologous letter. (The Lessenberry data were restricted to letters, with no information on substitutions involving punctuation.)

Note that the keyboard is not quite symmetric. Because of mechanical constraints on early typewriter design, the vertical columns are actually on a diagonal. This complicates the determination of homology for keys in the bottom row. It also permits us to contrast purely spatial symmetries with "movement symmetries."

For example, relative to the positioning of the hands at the keyboard, the letters m and c are in homologous positions, but the m is typed by the index finger and the c is typed by the middle finger. There were relatively few substitutions of m for c or c for m.

### At What Level Do Homologous Errors Occur

The confusion that leads to a homologous intrusion could conceivably occur at any of a number of levels: (a) in the selection of the motor program (the set of commands to muscle groups); (b) in the specification of the hand, finger, and finger position that determine the key to be typed; (c) within a more abstract representation of the keyboard (for example a spatial representation). These are clarified below.

A confusion of motor programs would result from a possible association between symmetrical movements. The special relationship between symmetric motions is manifest in the relative difficulty of making different motions with the hands -- it is more difficult to "pat your head and rub your stomach" than to pat or rub both.

A confusion at the "movement component" level could occur if keys are at some point specified in terms of hand, finger, and finger position, and if one of these components, in this case hand, is specified incorrectly. This differs from a confusion at the motor program level in that, for example, it could lead to the specification of three

components not typically associated, such as "right middle finger down and inward." Because the middle finger does not normally make such a movement, presumably no motor program has been formed for that particular movement, so such a confusion could not occur at the motor program level.

A confusion at the abstract representational level can be pictured by specifying keys with Cartesian coordinates on a grid that has one axis down the middle of the keyboard. A homology would occur if the "sign" of the "x" coordinate were reversed.

I argue that (a) is responsible for some, though not all, of the errors, and that (b) probably accounts for most. Although (c) could be made to account for some, there is no evidence that requires positing such a level of abstraction.

First, consider (a). If learned motor programs for letters are likely to be confused when they result in "mirror-image" or homologous movements, the failure to get m,c homologies is explained -- there are no learned "mirror-image" programs for these letters. A down-and-inward movement exists for the middle finger of the left hand and results in typing c, but there is no learned down-and-inward pattern for the right middle finger. So no confusion occurs. This also explains the v, n homology, but it runs into trouble with the relatively numerous v, m confusions. The motor programs for these should be quite different, one being inward and the other outward. There is a similar problem in explaining the b, n confusions, which outnumber even the v, n substitutions.

Explanation (b), a confusion of movement components, can explain the v,m and b,n confusions, assuming finger position specifications like "down" for m and v, and "down and inward" for n and b. This also explains the absence of m, c substitutions (different finger assignments). But it does not predict n, v homologies, which are even more common than those of m, v. Since n, v are motorically homologous, (b) and (a) together cover all of the errors.

The failure to find a m, c homology would eliminate (c), the confusion at the level of an abstract mental representation, if the typist's representation of the keyboard were an undistorted version of the actual keyboard. But imagine a representation in which the rows have been aligned, as in Figure 21. This alignment is a natural one, in that the keys in each column are typed by the same finger. In fact, when I gave skilled typists a set of loose keys and asked them to arrange them as on a keyboard, they invariably produced this pattern. Given this distortion, (c) is effectively indistinguishable from (b). (Below I show that it is also necessary to increase vertical separations relative to horizontal separations and to place a larger separation between the center alphabetic keys than between other keys to make the abstract representation useful. None of these is really implausible, but such a representation is not needed to account for any data.)

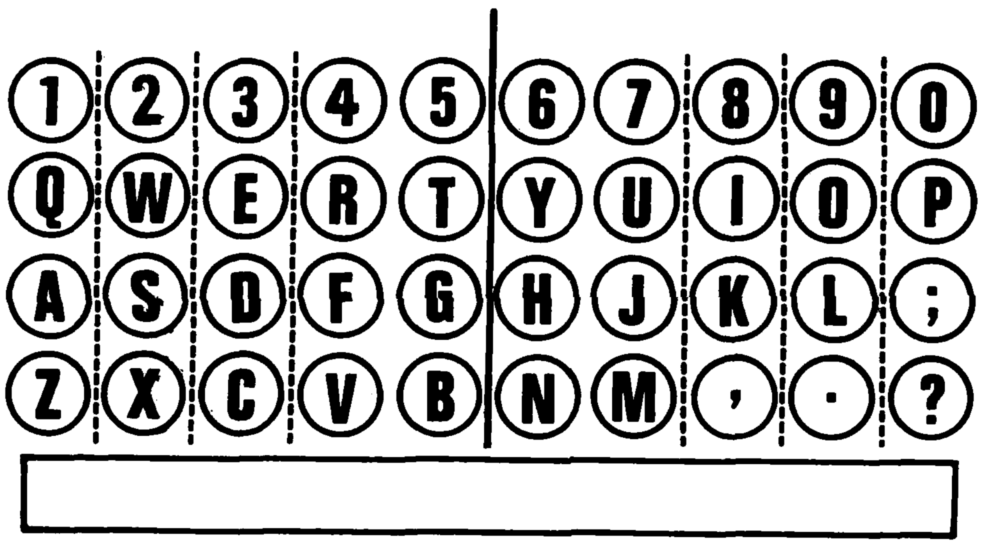


**Figure 21. A symmetric alignment of the keyboard.**

## Letter Frequency Effects

Consider the symmetry of homologous errors. Is one more likely to replace a left-hand letter with its right-hand homologue than to replace a right-hand letter with its left-hand homologue? Is one more likely to replace a lower-frequency letter with its higher-frequency homologue than a higher-frequency letter with its lower-frequency counterpart? I found no effect of hand, but a strong effect of frequency. For example, d has a higher frequency than its homologue k. The letter d was struck for k 484 times, while k was struck for d only 287 times. However, the absolute frequency of error is not the best test. For example, although o is more frequent than w, o was substituted for w only 104 times while w was struck for o 122 times. This is misleading, because the typists had fewer opportunities to err on w, since w was encountered less often. We need to control for letter frequency; that is, to examine the proportion of the occurrences of a letter that leads to a substitution. To allow such controlled comparisons, I constructed a normalized confusion matrix for each raw data matrix (see Appendix). After normalizing for letter frequency, it is always the case that higher-frequency letters are more likely to replace lower frequency letters in homologous substitutions.

## Summary of Lessenberry Data Analyses

The most common errors are the striking of keys immediately adjacent, either horizontally or vertically, to the intended key. Also highly frequent is the striking of the homologous or mirror-image key. The best explanation for most of the homologous errors is that the representation of a keystroke includes a specification of the hand to be used, and that an error in this specification leads to the homologous intrusion. Finally, a higher-frequency letter is more likely to be typed for a given lower-frequency homologous letter than vice versa.

Although the size of the corpus makes Lessenberry's data useful, we know little of the circumstances under which it was gathered. Russon and Wanons (1973, p 205) describe the typists as "students." For this reason, I constructed confusion matrices from the errors of novice and expert typists to corroborate and extend the above analyses.

## Novice and Expert Confusion Matrices

### Method

Six professional typists transcribed magazine articles totaling approximately 60,000 characters. In some sessions, typing was done on a computer keyboard with which the typists were familiar; in the others, on a Microswitch keyboard designed to look and feel identical with an IBM Selectric typewriter keyboard. The text was presented as double-spaced typed copy on individual sheets of paper. After a 10 minute warmup with another text, the typists were given an article and asked to transcribe it. They were told not to worry about errors and to type for speed. Keypresses and the corresponding times were recorded by a

microcomputer.

In addition, novice typists were recruited from the beginning typing classes at a local high school. Eight students spent one hour each week transcribing text on the Microswitch keyboard using the procedure just described. In addition, class papers were collected six weeks into the class, when the students had been acquainted with all letters of the keyboard for two weeks, and a three-paragraph exercise was scored for errors.

Some sessions of novice and expert typing were videotaped using a rotary shutter camera aimed down at the keyboard from above. Two views of the fingers were obtained by placing a mirror behind the keyboard at a 45 degree angle. By forming its image in less than 2 msec, the rotary shutter yields an image quite free of blur. The video fields were serially numbered with an electronic video counter and analyzed using a Sony video motion analyzer.

I undertook separate analyses of novice and expert data. Table 12 gives the typing speeds, error rates, and a categorization by purely descriptive error type for each skilled typist and for the novices as a group. (The typing speed for students is a good approximation; all rates are based on a 5-character word and make no correction for errors.)

Substitution, insertion, and omission errors all refer to single-letter errors in otherwise correctly typed words. Many of the miscellaneous ("other") novice errors are, in fact, words in which two substitutions appear to have been made. Thus, substitution errors completely dominate the errors of students. These are substantially reduced in experts, where they are the second most common error. Insertion errors, the most frequent for experts, are not necessarily the most interesting: the overwhelming majority of a randomly selected subset examined on videotape are misstrokes, two keys struck by one finger. For this reason, only substitution errors were used to generate confusion matrices. These included some 3300 and 500 substitutions for novices and experts, respectively.

Immediately adjacent keys of the same row accounted for 59% of the novice substitutions and 31% for the experts (compared with 43% for Lessenberry). Errors of the same finger in the same column were 8% of novice substitutions, 16% of experts, and 15% in Lessenberry's data. The proportion of substitutions that fit the description of homologous error were 4% for the experts and 16% for the novices. Lessenberry's data showed 10% of this type. Possibly Lessenberry examined intermediate typists or, more likely, a range of skill levels.

Homologous Substitutions

Chance level for producing homologous errors by random substitution of letters is about 3%. However, substitution errors are not random. Seventy-eight percent of skilled typist substitutions and 72% of novice typist substitutions are within hand. Restricting the analysis to 2H errors, homologies account for 17% of expert and 62% of novice errors (chance being 7%). Thus, there may be homologous substitution by skilled typists, though infrequently compared with novices.

Lessenberry's data were for letters only, leaving open the question of whether novices homologously confuse letters and punctuation -- the a and the semicolon, for example, or the c and comma. In my corpus there is no example of such an error. Punctuation is struck for adjacent letters -- the semicolon for the l, the comma for the m -- but never for the homologous key. Possible reasons for this are discussed in the next section.

Homologous errors by novices can be found in sequence or with an intervening key typed correctly, as in learn -> siarn and think -> thend.

Twenty-three homologous errors by eight novices were examined on videotape. In 18 cases only one finger moved. Twice, both fingers moved toward the homologous keys simultaneously. In three cases, the correct finger moved to the correct key, withdrew, and then the error was made. This indicates that the error is often, but not always, made early, more likely in the specification of the components of action than at the level of the motor program.

Frequency Effects in Homologous Errors

As we have seen, Lessenberry's data show a frequency effect. For each homologous letter pair, the higher-frequency letter is more likely to intrude in place of its mirror-image than vice versa. My study of novices confirmed the effect. Nine of the ten pairs showed the pattern. The set of substitution errors by skilled typists contained only 19 homologous mistakes and did not show the same pattern, with ten intrusions by higher-frequency keys and nine by lower-frequency keys.

Some of the homologous errors in their context indicate that multi-character response units may be represented during performance. In particular, homologous errors rarely create low-frequency digraphs. For example, the letter k appeared in three words in the novice typing exercise: stroking, think, and know. Students mistyped it as d 46 times. In the first two words, the substitution of a d produces no unusual letter combinations. These accounted for 45 of the 46 homologous errors. Only once did a typist type dnow, which includes the unusual digraph dn. Similarly, the word sequences was typed on different occasions with homologous errors in the second, third, fifth, and sixth positions, but not in the fourth, which would have produced the illegal digraph qr. In fact, substituting q for p, which would usually

form an illegal digraph, is proportionally the rarest homologous error in both Lessenberry's corpus and my own.

The effect of letter frequency -- that, in the move common novice errors, higher frequency letters are more likely to intrude -- may explain the failure to find homologous errors involving punctuation keys. Both punctuation keys and the letters in positions homologous to them are low in frequency (with one exception). Low frequency keys, by definition, seldom occur, so there is little chance for substitution. The exception, a, is homologous to the semicolon, which has extremely low frequency. Thus, semicolon is unlikely to replace a, and there are few opportunities for a to replace semicolon. Of course, other factors may be at work. For example, most homologies involving punctuation would create low or zero frequency digraphs, which, as we have seen, rarely occur in substitution errors.

## Adjacent-Letter Substitutions

Most substitution errors in both unskilled and skilled typing occur when an immediate neighbor of the target key is struck in its place. Every researcher investigating typing errors has noted the prevalence of these errors, particularly for horizontally adjacent keys. It is reasonable to suppose that these represent aiming or trajectory errors. On videotapes of skilled and novice typists, I located instances of substitution by a horizontally adjacent letter. I restricted the set to those in which the two keys would normally be typed by different fingers (e.g., small -> smsll, each -> wach, golf -> gold. In each case the intended and typed keys are adjacent on the keyboard but are struck by different fingers.

In these substitutions, the question is which finger strikes the key. For 22 of the 25 skilled typist errors and 42 of the 44 novice errors examined on videotape, the key was struck by the finger that usually strikes it. The errors could not be attributed to errant finger trajectories.

Thus, typists are more accurate in the execution of keystrokes than might have been supposed, but occasionally err in their specification of finger. This is the more interesting explanation, as it indicates that the finger to be used is explicitly represented during execution.

Column substitutions are a moderate source of error, accounting for 16% of novice and 8% of expert errors. Analysis of the videotapes to determine whether a finger strikes a key squarely or not is more difficult than determining which finger strikes a key, but in most cases it is clear. Of the 14 examples examined, in 8 cases there was a clean motion to the wrong key; 3 were misstrokes, landing between the keys, and the remaining three were difficult to judge. Thus it is likely that most vertical errors are also specification errors.

Immediate neighbors are much more likely to be substituted than distant letters in the same row or column. The data in Table 13 support this observation. Each number represents the median number of substitution errors within the pairs in the specified category. For example, the top row indicates that, for row substitution errors involving one finger (1F) and a distance between the correct and struck letter of one (i.e., they are immediately adjacent), Lessenberry's (normalized) data show the median number of substitutions to be 1521. This would be such pairs as r-t.

The next three rows of the table indicate that the likelihood of substitution falls off quickly with distance across the keyboard. These rows show pairs typed by two fingers of the same hand (2F) with separations of 1, 2, and 3 letters. Examples of these would be a-s, a-d, and a-f, respectively. The column errors show a similar effect of proximity.

Across-hand (2H) and diagonally adjacent pairs are included for comparison. For example, a 2H error of distance 1 is a substitution by an immediately adjacent key typed by the other hand, such as a t for a y. For 2H substitution errors of distances 1 and 3, the numbers are high because several pairs are homologous. Diagonal errors are notably fewer than either row or column adjacent errors, even in 1F diagonal confusions such as f-t, where hand and finger are constant. Perhaps diagonality is not a position equivalent to the vertical or horizontal. Alternatively, the paucity of errors could arise from the lack of diagonal movements of the other fingers, and a consequent reduced probability of a confusion in this specification.

Given the relatively few 2H errors, physical proximity alone is not adequate to explain the predominance of substitutions of immediately adjacent neighbors. Neighboring fingers share musculature, and postural compensations for finger movements may be similar for neighboring fingers. As was argued above from the pattern of homologous errors, the confusion probably occurs at the level of the movement components of hand, finger, and finger position, or at the lower level of the motor program itself.

## Frequency Effects in Adjacent Errors

As with homologous errors, there are large frequency effects in adjacent errors in Lessenberry's data. Once again, after normalizing for frequency in the language, a typist is more likely to substitute a higher-frequency letter for a neighboring low-frequency letter than vice versa. This asymmetry held for every pair of row adjacent keys and 15 of 16 pairs of column adjacent keys.

We are now in a position to use the disproportionate likelihood of immediately adjacent letter intrusions to explain why MacNeilage (1964) found a preference for substituting home row keys. Home row keys have two adjacent vertical neighbors, while keys on the upper and lower rows have only one. Thus, there is no intrinsic preference for the home row.

(Other data of MacNeilage can be explained by this frequency effect as well.)

The frequency effect was confirmed in my novice study, with 31 row or column adjacent pairs favoring the higher-frequency letter and 7 pairs favoring the lower-frequency letter (chi-square (1) = 22.04, $p < .01$). Because the skilled typists made proportionally fewer row and column errors, as well as fewer errors overall, their data are noisier, with many empty cells. Of those pairs with one or more substitutions each direction, 18 favor the higher-frequency letter (after normalization) and only 6 favor the lower frequency letter, a significant difference (chi-square(1) = 5.04, $p < .025$).

We can eliminate the possibility that the frequency effects result from the typist's more careful scrutiny of relatively unfamiliar low-frequency keys during plerformance. Such scrutiny could lead to early detection of potential errors in which low-frequency letters are about to be typed. However, the relatively high proportion of substitutions within pairs such as z,x and j,k suggests that low-frequency letters do not get particularly careful inspection before they are typed. Thus it is more likely that intrusion by the higher-frequency letter brings about the substitution error.

## Permutation Errors

Novices and experts show different patterns of letter transpositions. Experts average around 80% across-hand transpositions, and almost always exchange two successive letters from the text. Only twice in the corpus did a letter migrate across more than one position (deliberately -> deliberatyel, outweigh -> ouweight), and only once did letter "components" appear to switch (simple -> simo;e). Although a world champion typist (Owen, 1919) reported that she eventually began to transpose words rather than letters, our typists did this only twice. More common were "interchanges," the switching of two separated letters, such as big -> gib, figuring -> firuging, and the more complicated examples denomination -> demonimation and and more -> amd nore. As the examples indicate, these were almost all within-finger errors.

Novices are almost as likely to make within-hand as across-hand transpositions (40% vs. 60%). They are more likely than experts to transpose homologous letters (25% vs. 12% of 2H transpositions). Novices, more than the experts, move a key past two intervening keys (for example, sequences -> squeences, lower -> leowr). Every novice permutation falls into one of three categories: transpositions, interchanges, and migrations across two positions. (These constitute fewer than half of the theoretically possible permutations.)

The data suggest that migrations and most transpositions involve one mechanism and interchanges a different mechanism. Most transpositions involve non-homologous 2H letter sequences. In contrast, interchanges (e.g., major -> jamor, also -> aosl) by experts and novices are generally 1F: the two keys involved (but not the intervening key) are

typed by the same finger. Hand and finger, two of the three principal components determining a keystroke, are shared. Most of the remaining interchanges are 2F and involve row adjacent keys, and again two components are shared: hand and position. Finally, of the few 2H interchanges, most involve homologous keys, sharing finger and position.

In a videotape study of 66 transposition errors, I found that, for both novices and experts, the finger that made the first motion toward the key was usually the finger that first struck a key. Thus, the reversal may typically occur early in execution.

Learning. To determine the effects of practice, I examined a sample of novice typing taken one month later. In this extra month, the novices had 67% more experience with typing and up to three times the experience with the last keys introduced in the class.

As expected, performance was generally closer to but not equal to expert performance. There are fewer errors overall. Twenty-eight percent of all transpositions are within-hand. Homologous reversals account for 29% of 2H transpositions, which is still more than skilled typists. The misplacement of a letter by more than one position is rarer than before, bringing the students in line with expert performance in this regard. Interchanges still occur, and as before, usually involve keys sharing two of the three movement components of hand, finger, and finger position.

## Other Errors

Norman (1981) uses the term "activation error" to describe an error in which a similar but more common or more recent performance is substituted for the behavior one had intended. A number of errors made by skilled typists seem to be of this sort. In the error Even experts -> Even Experts the space-e sequence in " experts" may have reactivated the space-shift-e sequence. Another example is the mistyping of "chew everything carefully, never gulp" into "chew everything carefully, nevery gulp."

Substitution errors not yet accounted for include a large number of vowel-for-vowel substitutions (even after normalizing for their high frequency of occurrence), and confusions of the letters c,g,s,t,w. Both may represent an activation of a multi-letter response unit, perhaps one recently active, by the presence of component letters. In the case of the five consonants, the units could be digraphs ending with the letter h. Thus, most substitutions of the five consonants (except s with w, those being adjacent keys) are in such cases as Ruth -> Ruch, Rugh; three -> chree; show -> whow; check -> sheck; etc.

Misstrokes, which are not a major source of substitution errors, are more evident in instances where an extra letter is inserted into the text -- a finger strikes two keys simultaneously. Well over half the insertion errors by experts are potentially such errors, and most examined on videotape are two keys struck by the same finger. In other

cases, the finger adjacent to the key being struck moves along with it and hits a key, causing an insertion. These two mechanisms account for all the examined insertions by Typist 3, who alone accounts for over half of all insertion errors by skilled typists. One skilled typist (Typist 5), whose retraction from striking the space bar normally causes her right middle finger to skim close to the k, actually strikes it occasionally -- but only when the letter about to be typed is a p -- the motion toward the p on top of the retraction from the space bar causes the middle finger to hit the key. Her only insertions of the letter k thus comes before words beginning with p.

Most insertion errors of the misstroke description occur when an index finger is reaching inward or diagonally for one of the six center keys. Many insertions that do not appear to be misstrokes consist of typing a letter that appears elsewhere in the word, usually later. For example, fiber -> bfiber, crash -> cracsh. However, this is true for only two of the six typists. These two typists are shown elsewhere (Gentner, 1981a) to have particularly independent finger movements, leading to more overlapping finger motion. There are several possible explanations. With a number of fingers approaching keys simultaneously, anticipatory keystrokes might be more likely. Also, these errors could be transpositions, interchanges, or migrations that were subsequently corrected. (Examples, are notion -> ntotion, ravenous -> vravenous.)

Errors of omission by skilled typists follow the general serial position pattern described by MacNeilage (1964) for errors of this type: they are rare in the first letter position and most common in the next few positions. Videotape analysis indicates that for approximately half, there is no motion toward the omitted key. When there is motion toward the key, it varies in its degree of completion: at times the finger seems to contact the key, while at other times the finger simply moves over the key but never strikes at it. We note in Gentner, Grudin, and Conway (1980) that there are often two clearly delineated parts to a keystroke: the motion toward the key and a rapid downstroke. On still other occasions the finger positions itself over the key and makes a very weak thrust in the direction of the key, coming nowhere near it. I see no pattern to these different responses.

Omitted letters are likely to appear, typed correctly, in the word preceding or following the word being typed, or elsewhere in that word itself. (For example, three typists omitted the third i in artificial.) This was true for over 60% of all omissions. In the video study the letter is significantly more likely to precede the omission; in another study the letter is almost equally likely to follow the omission. Omissions of one of a double-letter pair occurred only 17 times, but this is 20% over chance based on the percentage of doubles in the text.

The low incidence of omissions in the first letter position in a word suggests that that letter is particularly strongly activated, and for that reason possibly subject to less noise. Therefore, I looked particularly carefully at the 31 omissions that did occur in the first position. In 42% of them, the omitted letter was also one of the 3

preceding letters, usually the immediately preceding letter, as when "the entire" was typed "the ntire" or "keep putting" was typed "keep utting." In many of the remaining omissions, the finger previously used was the finger that should have typed the omitted letter. For example, three words dropped an initial p or l when immediately preceded by a carriage return, which uses the same finger. This suggests that the "deactivation" of a letter for motor program following a keystroke has, in these cases, interfered with the typing of a subsequent key.

There were a small number of doubling errors, in which the wrong letter is doubled (for example, well -> weel, and just one error fitting the description of an alternation error (where -> whrer), by Typist 3. The alternating sequence ere is one of the fastest of the 124 alternating sequences in the text for Typist 3, despite being within-hand.

Lashley (1951), Shaffer and Hardwick (1968), and Rumelhart and Norman (1982) argue that doubling and alternation errors indicate the use of special markers for such sequences -- when the marker is applied to the wrong letter an error occurs. The omission errors suggest why such special measures may be necessary -- without them, the deactivation process following a keystroke would interfere with the quick retyping of the same key.

## The Development of Skilled Typing

In this section, I summarize the results of the investigations of typing errors and discuss the implications as they bear on three developmental changes in error patterns: (a) the disappearance of homologous errors with the acquisition of skill; (b) the reduction in the proportion of adjacent substitution errors; (c) the marked increase in the percentage of across-hand transpositions.

The major categories of substitution error are row, column, and homologous errors. In most cases, the error is due to a deliberate stroke by the finger appropriate for the key actually struck, with no motion toward the correct key. Thus, these errors are best explained as occurring prior to the active involvement of the motor program, when the keystroke is specified in terms of hand, finger, and finger position. For touch typists, this mapping of finger to key is particularly orderly. In those errors where two fingers are in motion simultaneously, the confusion may have occurred later, possibly among motor programs.

Although novices make more errors than experts, their errors are orderly. The majority are substitution errors, of which 75% are substitutions of immediately adjacent keys. Fifty-one percent of the remainder are homologous errors. Experts make proportionally fewer substitution errors, and fewer of them are adjacent keys. Skilled typists make very few homologous errors.

Evidence for multi-character response units in skilled typing, digraph units in particular, is presented elsewhere (Grudin, 1981). These units may help optimize postural and positional adjustments across a series of movements. As digraphs are relied on more heavily, substitutions based primarily on errors in hand, finger, and finger position specification may decline, as they often produce sequences of low or zero frequency. And movement "components" governing hand, wrist, and arm could come into play with the development of digraph response units. The greatest violation of such global preparations is a keystroke by the wrong hand, so homologous errors drop off quickly. Vertical movements require wrist and arm motion, so column errors would conflict with such preparation more than row errors. Among row errors, those of the same finger are most compatible, those of adjacent fingers reasonably compatible, but those of distant fingers might require different postural adjustments, and thus be less likely to occur. This parallels the distribution of these errors.

The pattern of substitution errors is marked by strong frequency effects. A higher frequency letter is more likely to substitute for a lower frequency neighbor or homologue than vice versa. This appears to result from an intrusion of the more common letter, which in an activation model could yield to either a recency or frequency explanation. A long-lasting, residual activation could follow the typing of a key; keys active more recently or more often would have more residual activation. Alternatively, the activations for higher-frequency elements could have higher resting levels or lower thresholds for initiating action.

Residual effects of deactivation are indicated by the pattern of omission errors. A letter is more likely to be omitted if the same letter was recently active (and thus recently deactivated). This suggests that deactivation may be a source of variability in typing: When a letter is insufficiently deactivated, a substitution error may follow, whereas when a letter is too strongly deactivated, the same letter appearing soon afterwards may fail to be typed.

In addition, omissions are strongly influenced by serial position within the word being typed, with initial letters least likely to be omitted and medial letters most likely. This matches other determinations of the relative strengths of letters, and suggests an initial profile of letter activation.

For novices and experts, all errors in which the correct letters are permuted result from either the misplacement of a single letter or the switching of two letters. The great majority of these are either transpositions or interchanges, with the former more frequent. Interchanged letters almost always share components, most often being two letters typed by the same hand and finger, while transpositions are typically typed by different hands. A possible reason is that transposed letters are part of a multi-character response unit, while interchanged letters belong to different response units.

Elsewhere I argue from the timing of transposition errors the presence of centrally issued "trigger" pulses for the two letters involved (Grudin, 1981). Thus, within a unit, subordinate letters may be transposed because keystroke times have little flexibility. If one finger is out of position, another finger might come in early. Transpositions are likely to be 2H for several reasons: in such a sequence, a movement or mispositioning of one hand can influence one finger while not affecting the other; the second letter has more freedom to reach its key early if it is on a different hand; interstroke intervals are shorter for 2H sequences, and the activation levels guiding the keystrokes may accordingly be more equal. If interchanges, by contrast, involve two response units, they are free of these timing constraints, and are more likely to be affected by response similarities of the letters involved.

The different patterns of transposition errors in the typing of novices and experts may be due to the greater reliance of skilled typists on multi-character response units. Novices transpose two letters typed by the same hand twice as often as experts. This is consistent with the argument that the prevalence of 2H transpositions in skilled typing is due to constraints on timing within multi-character sequences (Grudin, 1981). Some novice transpositions may be interchanges involving single-character response units, interchanges with no intervening letter. Just as interchanges involve keys sharing components, 69% of 1H novice transpositions are horizontally or vertically adjacent letters, and 25% of the 2H cases are reversals of homologous keys. Thus, 41% of novice (and only 16% of expert) transpositions share two of the hand, finger, and finger position specifications.

The remaining novice 2H transpositions may, in fact, represent multi-character sequences already being learned. Over half of them are in function words <u>the</u>, <u>that</u>, <u>than</u>, <u>for</u>, <u>to</u>, and <u>and</u>. The average length of a word containing a 2H transposition is under 4 letters, while the length of a word containing a 1H transposition averages over 6 letters. A similar effect holds for our experts. Words containing 2H transpositions average 6.1 letters while words with 1H transpositions average 7.8 letters. This significant difference results from the absence of short words containing 1H transpositions: there are 21 2H and no 1H errors in words of two and three letters (there are many 1H function words, such as <u>are</u>, <u>as</u>, <u>at</u>, <u>be</u>, <u>in</u>, <u>on</u>, and <u>was</u>). Short words may be executed as units, less susceptible to the errors based on shared components (which includes most 1H errors) that I associate with errors across response units. This analysis also suggests that longer words are not executed as units.

Are these multicharacter response units "syllables"? Shaffer (1975) reported that most transpositions occur within a syllable. This was true for 91% of our transpositions of letters. However, 87% of all letter-letter transitions are within-syllable in the text. The difference is not significant, so transpositions provide no evidence for syllable representation in typing.

There is further evidence that novices have begun abstracting patterns. The special treatment of double letters, inferred by Lashley (1951), Shaffer and Hardwick (1968), and Rumelhart and Norman (1982) from the existence of errors such as ill -> iil, is indicated by such novice errors as speed -> spped, spiid, and letter -> leteer, lettee, lettrr. But novices also produce errors such as speed -> spede and letter -> lerter, which suggest they do not always do so.

When novices move a letter past two intervening letters, as in that -> atht, the skipped letters are usually digraphs with high frequency or high transitional probability -- th, or, at, qu. This raises the question of why I found no transpositions of multi-character sequences in skilled typing. Two-letter insertions, omissions, and even substitutions occur (though much less frequently than single-letter errors), but not multi-character transpositions. Possibly typists strongly inhibit the activation of distant multi-character units. Most likely, typists would detect errors involving such large sequences before they complete. Typists do detect most errors during execution, virtually always within one or two letters of the error (Long, 1976; Rabbitt, 1978). If detected following one keystroke, a partly-executed digraph transposition would appear as an anticipatory insertion. If detected following two keystrokes, it might appear as a two-letter omission.

## Summary

Studies of the errors made during transcription by novice and skilled typists allow the correction and extension of previous analyses of typing errors, with implications for representation at various levels of the motor system during performance. Videotape records suggest that a keystroke is explicitly represented in terms of the hand, finger, and finger position that uniquely specifies it, and that a common source of error is the incorrect assignment of one of these three components. Further analyses provide support for previous indications that multi-character response units, notably digraphs, are represented during execution, and that certain errors occur within, and other errors across, such units. The formation of such multi-character units could explain differences in the patterns of novice and expert errors. Finally, the special problems arising from "deactivation" of representations to avoid perseveration may explain other errors, as well as mechanisms developed to avoid them.

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